SECURITY INFORMATION

~~CONFIDENTIAL~~

COPY 263
RM E51E03

[redacted]

NACA

RESEARCH MEMORANDUM

ALTITUDE INVESTIGATION OF 16 FLAME-HOLDER AND FUEL-SYSTEM CONFIGURATIONS IN TAIL-PIPE BURNER

By Ralph E. Grey, H. G. Krull, and A. F. Sargent

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

Classification cancelled (or changed to UNCLASSIFIED)

By Authority of NASA Tech Pub Announcement #9
(OFFICER AUTHORIZED TO CHANGE)

By .... 29 Sep 58
NAME AND

....
GRADE OF OFFICER MAKING CHANGE)

12 Mar 61
DATE

CLASSIFIED DOCUMENT

This material contains information affecting the National Defense of the United States within the meaning of the espionage laws, Title 18, U.S.C., Secs. 793 and 794, the transmission or revelation of which in any manner to unauthorized person is prohibited by law.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

December 12, 1951

~~CONFIDENTIAL~~

319.98/13

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

ALTITUDE INVESTIGATION OF 16 FLAME-HOLDER AND FUEL-SYSTEM CONFIGURATIONS IN TAIL-PIPE BURNER

By Ralph E. Grey, H. G. Krull, and A. F. Sargent

2176

SUMMARY

An investigation was conducted in an altitude chamber at the NACA Lewis laboratory to determine the performance of 16 flame-holder and fuel-system configurations in a short converging conical tail-pipe burner having a two-position exhaust nozzle. During the investigation, the engine was operated at rated engine speed, at a constant flight Mach number of 0.6, and over a range of tail-pipe-burner fuel-air ratios and altitudes.

Of the various configurations investigated, the best combustion performance and operable limits were obtained with a V-gutter flame holder and a radial fuel-injection system that provided a uniform fuel distribution over the flame holder and an increased mixing length between the fuel injectors and the flame holder. The maximum altitude limit obtained with one of the V-gutter flame holders was about 58,000 feet. The combustion efficiency, exhaust-gas temperature, and specific fuel consumption were only slightly affected by increases in altitude to 40,000 feet. The maximum altitude limits of the H-gutter and the H-gutter with a trailing V-gutter flame holders were 40,000 and 44,000 feet, respectively. The combustion efficiency and exhaust-gas temperature decreased and the specific fuel consumption increased rapidly with an increase in altitude for these configurations. With the jet nozzle open, starting by spark plug ignition was limited to altitudes of 30,000 feet and lower, whereas starts by the hot-streak ignition technique were obtained at all altitudes up to 45,000 feet, which was the maximum altitude at which starts were attempted.

INTRODUCTION

The altitude performance and operating characteristics of several types of flame-holder and fuel-injection system installed in the tail-pipe burner of a J35-A-21 turbojet engine were investigated in a 10-foot altitude test chamber at the NACA Lewis laboratory. The purpose of this investigation was to obtain a flame-holder and fuel-system configuration that would provide efficient combustion in a relatively short tail-pipe burner up to altitudes of at least 40,000 feet. Sixteen flame-holder and fuel-system configurations were investigated; ten configurations were supplied by the engine manufacturer and six were designed by NACA (based on information in reference 1). The tail-pipe burner, which was supplied as part of the engine, had a short converging conical burner section and a two-position exhaust nozzle. The outer shell of the tail-pipe burner remained unaltered during the investigation. Each configuration was operated over a range of altitudes at a flight Mach number of 0.6. 2176

The data obtained for each configuration are presented in a manner to show the effects of fuel distribution and flame-holder design on net thrust, specific fuel consumption, exhaust-gas temperature, combustion efficiency, operable range of tail-pipe-burner fuel-air ratios, and maximum altitude limit. The combustion stability during tail-pipe-burner operation is also described and typical flame-holder failures that occurred during the investigation are discussed.

APPARATUS AND INSTRUMENTATION

Installation

The engine was installed in an altitude chamber as shown in figures 1 and 2. The engine was mounted on a thrust platform, which was connected through linkage to a calibrated balanced air-pressure diaphragm for measuring the thrust. The altitude chamber is 10 feet in diameter and 60 feet long. A honeycomb is installed in the chamber upstream of the test section to straighten and smooth the flow of inlet air. The forward baffle, which incorporated a labyrinth seal around the forward end of the engine, was used to separate the engine-inlet air from the exhaust and to provide a means of maintaining a pressure difference across the engine. A 14-inch butterfly valve was installed in the forward baffle to provide cooling air for the engine compartment. The rear baffle was installed to act as a radiation shield and to prevent recirculation of exhaust gases about the engine. The exhaust gas from the jet nozzle was discharged into an exhaust diffuser to recover some of the kinetic energy of the jet. Combustion in the burner was observed through a periscope located directly behind the engine.

Engine and Tail-Pipe Burner

A J35-A-21 engine, which includes a tail-pipe burner, was used in this investigation. The engine has a static sea-level thrust rating of

5100 pounds without tail-pipe burning at rated engine speed, 7900 rpm, and at a turbine-outlet temperature of 1300° F. At this operating condition, the air flow is approximately 86 pounds per second and the fuel consumption is 5740 pounds per hour. The over-all length of the engine
2176 is approximately 195 inches and the maximum diameter is 43 inches. The main components of the engine are an 11-stage axial-flow compressor, eight cylindrical through-flow combustors, a single-stage turbine, and a tail-pipe burner. Throughout the investigation, MIL-F-5624 fuel with a lower heating value of 18,900 Btu per pound and a hydrogen-carbon ratio of 0.179 was used in the engine and tail-pipe burner.

Drawings of the tail-pipe-burner assembly are schematically shown in figure 3. The tail-pipe-burner assembly was $87\frac{1}{2}$ inches long and consisted of three sections: (1) an annular diffuser followed by a short cylindrical section, (2) a converging conical burner, and (3) a two-position clamshell-type exhaust nozzle. The eyelids on this nozzle were secured in the open position throughout the investigation. The area of the exhaust nozzle in the open position was approximately 349 square inches. Fuel was supplied to the tail-pipe burner by an air-turbine fuel pump which was driven by air bled from the compressor.

Two flame-holder positions and two diffuser inner cones were used during the investigation. Flame-holder position 1 and the standard diffuser inner cone are shown in figure 3(a). Flame-holder position 2 and the modified diffuser inner cone are shown in figure 3(b). Position 1, which was the standard location for the engine manufacturer's flame holders, was located in the 6-inch cylindrical section about $2\frac{1}{2}$ inches downstream of the diffuser-outlet flange. Position 2 was located in the diffuser section about 4 inches upstream of the diffuser-outlet flange. The modified diffuser inner cone consisted of a standard diffuser inner cone cut off at the downstream end where the diameter was 6 inches and a cup section having a depth of $3\frac{1}{8}$ inches was installed at this point to provide a sheltered region for burning. The details of the flame holders and fuel systems will be discussed later.

Shell cooling of the burner section was accomplished by an ejector cooling shroud, which used the exhaust jet to induce a flow of cooling air over the burner shell. In the present investigation, the air for the burner cooling shroud was obtained from the test section of the altitude chamber at a pressure approximately equal to the altitude ambient pressure and at a temperature of about 100° F.

Two types of tail-pipe-burner ignition system were used. For the 10 manufacturer's configurations, ignition was provided by two spark plugs projecting into the sheltered region of the outer annular gutter. For the NACA configurations, ignition was provided by a momentary increase in fuel flow to one of the engine combustors (reference 1). This excess fuel in one combustor caused a burst of flame through the turbine, thereby igniting the tail-pipe-burner fuel.

2176

Flame Holders and Fuel Systems

Ten commercial flame-holder and fuel-system units (figs. 4 and 5), four NACA flame holders (fig. 6), and four NACA fuel-injection systems (fig. 7), in various combinations were investigated in the 16 configurations presented in this report. These configurations are classified into five basic types:

(1) H-gutter flame holder with radial and annular fuel-injection manifold, configurations A through D

(2) H-gutter flame holder with trailing V-gutter and radial and annular fuel-injection manifold, configurations E through I

(3) Annular V-gutter flame holder with radial and annular fuel-injection manifold, configuration J

(4) Annular V-gutter flame holder with radial fuel injectors, configurations K through O

(5) Radial V-gutter flame holder with radial fuel injectors, configuration P

The flame-holder and fuel-system units of configurations A through J were supplied by the engine manufacturer. The H-gutter of configurations A through I consisted of two parallel sides connected by a cross-member with holes to meter fuel and air into the sheltered region downstream of the flame holder. The annular trailing V-gutters (typical installation shown in fig. 4(d)) had an included angle of 36°, were $1\frac{1}{2}$ inches wide, and had a diameter generally intermediate between the diameters of the two annular H-gutters. The flame holder of configuration J was constructed of V-gutters. The fuel for these configurations was injected through radial and annular tubes immediately upstream of the flame holder.

The fuel system of configuration K and the fuel-system and flame-holder configurations L through P were NACA designs. All flame holders for these configurations were constructed of V-gutters. The fuel for these configurations was introduced normal to the direction of gas flow through radial fuel injectors.

A detailed description of each configuration is presented in table I. A comparison of the five basic configuration types is shown in the following table:

Configuration		Flame holder				Fuel system		
Type	Figure	Gutter cross section: Type	Gutter cross section: Figure	Projected blocked area (percent)	Remarks	Fuel mixing length (in.) (a)	Injector figure	Remarks
1	4(a) and 4(b)	H	5(a) to 5(c)	25.5 to 30.9	2 to 3 annular gutters	1/8 to $1\frac{5}{8}$		Annular tubes connected by radial tubes
2	4(c) to 4(f)	H-V	5(b) 5(d) and 5(e)	36.2 to 43.3	2 annular H-gutters with 1 or 2 trailing V-gutters 4 to 6 inches downstream	7/8 to $1\frac{7}{8}$		Same
3	4(g)	V	5(f)	28.9	2 annular gutters	$6\frac{1}{2}$		Same except tubes were streamlined
4		V	6(a) to 6(c)	28.9 to 35.2	2 annular gutters	3 to 10	7(a) to 7(c)	Radial tubes
5		V	6(d)	26.6	Short radial gutters connected by one annular gutter	$5\frac{5}{8}$	7(d)	Radial tubes

[a]Mixing length is defined as distance from point of fuel injection to leading edge of flame holder.

Each part of the flame holder and fuel system is numbered on the photographs of figure 4 (configurations A through J) and details of the corresponding part are given in table II.

Instrumentation

Pressures and temperatures were measured at several stations in the engine and tail-pipe burner (fig. 2). Engine air flow was measured by use of survey rakes mounted at the engine inlet. Pressure and temperature instrumentation was installed to compute engine midframe air bleed and the air bled from the compressor outlet that was used to drive the air turbine of the tail-pipe-burner fuel pump. A complete pressure and temperature survey was obtained at the turbine outlet (station 5, fig. 8(a)), and several of the 30 thermocouples at station 5 were used to obtain an indicated turbine-outlet temperature during operation. Static pressure measurements were taken at the burner inlet (station 6, fig. 8(b)) and total pressures were measured with a water-cooled survey rake at the exhaust-nozzle inlet (station 7, fig. 8(c)) 5 inches upstream of the exhaust-nozzle outlet. Engine and tail-pipe-burner fuel flows were measured by calibrated rotameters.

PROCEDURE

Tail-pipe-burner performance data were obtained over a range of tail-pipe-burner fuel-air ratios at a simulated flight Mach number of 0.6 and the following simulated altitudes:

Altitude (ft)	Configuration															
10,000	A	B	C	D				H		J		L			O	P
30,000	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
35,000				D	E											
40,000		B			E			H		J	K	L	M	N	O	P

The engine-inlet-air total temperature and total pressure were regulated to correspond to NACA standard total temperature and pressure assuming 100-percent ram pressure recovery at each flight condition.

The symbols used in this report and the methods used in calculating the results are given in the appendix. Due to a questionable radiation effect on the thermocouples at the turbine outlet, the turbine-outlet temperature was calculated as shown in the appendix. This calculated temperature was used in plotting all curves presenting turbine-outlet data. Two fuel-air ratios are defined and used in computing and plotting the results of the investigation:

(1) The tail-pipe-burner fuel-air ratio $(f/a)_t$ is defined as the ratio of the tail-pipe-burner fuel flow to the engine air flow (air flow entering the compressor minus air bled from the compressor). This fuel-air ratio was used when only flight condition, rpm, and tail-pipe-burner fuel flow were recorded. The values of engine air flow were taken from an engine air-flow calibration curve.

(2) The unburned-air tail-pipe-burner fuel-air ratio $(f/a)_{ua}$ is defined as the ratio of the tail-pipe-burner fuel flow to the unburned-air flow entering the tail pipe (engine air flow minus the air burned in the engine). This fuel-air ratio was used when complete performance data were obtained.

The tail-pipe burner was started at a simulated flight Mach number of 0.6 and rated engine speed of 7900 rpm with the exhaust nozzle in the open position. For altitudes up to 30,000 feet, the tail-pipe burner was ignited and performance was obtained over a range of tail-pipe-burner fuel-air ratios. At altitudes above 30,000 feet, the tail-pipe burner was ignited at 30,000 feet, the simulated altitude was increased to the desired value, and data were obtained over a range of tail-pipe-burner fuel-air ratios.

At each flight condition with the engine operating at rated speed, the tail-pipe-burner fuel flow was varied from a minimum to a maximum. The minimum fuel flow was determined by: (1) imminent blow-out, or (2) a control limit (minimum flow rate of standard engine fuel regulator). The maximum fuel flow was determined by: (1) the indicated limiting turbine-outlet temperature of 1300° F (1760° R) measured by the operating thermocouples at station 5, (2) control limit (maximum flow rate of fuel regulator), (3) rough burning, or (4) blow-out. To determine the maximum operable altitude the burner was operated at constant fuel flow and flight Mach number while altitude was increased until blow-out occurred. Because actual blow-out of the burner was usually quite sudden, operating technique may account for scatter in the data of about ±2000 feet.

RESULTS AND DISCUSSION

Operational Limits

The operational limits of all configurations are plotted in figure 9 against the tail-pipe-burner fuel-air ratio $(f/a)_t$. The four kinds of operational limits encountered, which were discussed in the procedure, are defined by the symbols of figure 9. For configurations A, B, C, and O, the maximum operable altitude was not determined but it is believed that this limit was generally about the same as the altitude limit obtained for other configurations of the same basic type. The performance data and operational limits were not obtained at an altitude of 10,000 feet for some configurations because the flame holder was extremely hot and the service life under these conditions was very short.

The maximum altitude limit for basic configuration types 1 and 2 was generally about 40,000 feet with configurations E and H (basic type 2) reaching 44,000 feet. The altitude limit of basic configuration type 3 was about 45,000 feet, whereas that of basic types 4 and 5 was generally above 50,000 feet with configuration M (basic type 4) reaching 58,000 feet.

The rich operational limits of basic configuration types 1 and 2 generally resulted from blow-out, rough burning, or fuel-regulator limitations, whereas configuration types 3, 4, and 5 were restricted by limiting turbine-outlet temperatures. The occurrence of this limiting turbine-outlet temperature condition at relatively low fuel-air ratios indicates that basic configurations types 3, 4, and 5 were operating at higher combustion efficiencies than configuration types 1 and 2.

With the exception of configuration A, rough burning was encountered with all H-gutter configurations at rich fuel-air ratios. Rough burning would start suddenly with an attendant increase in noise level and vibration. When the fuel-air ratio was increased after rough burning was encountered, the noise level and vibration increased. An examination of the tail-pipe burner after such operation revealed broken and loosened bolts. In general, blow-out of basic configuration types 1, 2, and 3 was characterized by the flame shifting to the lower half of the flame holder and gradually diminishing until blow-out, whereas in configuration types 4 and 5, blow-out occurred suddenly.

A comparison of the operational limits of configurations B, H, J, L, and P, which represent the best operational limits and performance characteristics of each of the five basic configuration types, is shown in figure 10. Although configuration C appeared to be better than configuration B, it was not used for this comparison because the engine-inlet total temperature was 23° to 37° F below the NACA standard total temperature for all data obtained at an altitude of 30,000 feet.

Of all the configurations investigated, basic configuration types 4 and 5 had the highest altitude limits. An evaluation of these data indicates that the altitude limit was increased by the combined effects of (1) radial fuel injection with uniform distribution over the flame holder, (2) increased fuel mixing length, and (3) a V-gutter instead of H-gutter flame holder.

2176

Performance Characteristics

The performance data obtained for each of the 16 configurations with a fixed-area conical exhaust nozzle is presented in table III. Performance data for five configurations, B, H, J, L, and P, are summarized in figures 11 through 16. These configurations were previously indicated to have the best operational limits and performance characteristics of each of the five basic configuration types. Performance data were plotted against the unburned-air tail-pipe-burner fuel-air ratio $(f/a)_{ua}$. With the exhaust nozzle fixed in the open position, the burner-inlet conditions varied with fuel-air ratio as shown in figure 11. In general, the turbine-outlet total temperature and pressure increased with tail-pipe-burner fuel-air ratio, whereas the burner-inlet velocity remained approximately constant. The turbine-outlet temperature survey used during operation for part of the investigation was found to be insufficient when later compared to the average of 30 thermocouples at station 5 and to the calculated value of turbine-outlet temperature. Consequently, some configurations were operated above limiting temperature. In such cases, the limiting turbine-outlet temperature operating point is indicated on the curves.

A comparison of combustion efficiencies and exhaust-gas temperatures for the five representative configurations over a range of fuel-air ratios at various altitudes is shown in figure 12. At an altitude of 30,000 feet and limiting turbine-outlet temperature (1760° R), configuration type 4 reached a combustion efficiency of 72 percent at a fuel-air ratio of 0.035 and a peak combustion efficiency of 85 percent was obtained at a fuel-air ratio of 0.021. In comparison, at this same altitude and at a peak turbine-outlet temperature of 1660° R, the combustion efficiency obtained with the configuration type 1 was 32 percent at a fuel-air ratio of 0.07 and a maximum combustion efficiency of 54 percent was obtained at a fuel-air ratio of 0.023. The peak combustion efficiency of all configurations occurs at higher fuel-air ratios as altitude is increased. The peak combustion efficiency is shown to decrease rapidly with increasing altitude for configuration types 1, 2, and 3 but to decrease only slightly for configuration types 4 and 5. The effect of altitude on exhaust-gas temperature was to decrease the temperature at a constant fuel-air ratio or to increase the fuel-air ratio required to maintain a constant temperature as altitude was increased. These trends were considerably greater for configuration types 1, 2, and 3 than for 4 and 5. The rate of increase in exhaust-gas temperature with fuel-air ratio became less after peak combustion efficiency had been reached. At all altitudes, the values of combustion efficiency and exhaust-gas temperature at a given fuel-air ratio were higher for configuration types 4 and 5 than for types 1, 2, and 3.

In some cases there were significant changes in combustion efficiency among the configurations within a given basic type. At an altitude of 30,000 feet, where data were obtained for all configurations, the maximum combustion efficiency of the type 1 configurations varied from 51 to 66 percent and generally occurred at a fuel-air ratio of about 0.025. Maximum efficiency variation among type 2 configurations was somewhat greater, ranging from 57 to 66 percent and occurring at a fuel-air ratio of about 0.023. Among the type 4 configurations, peak efficiency varied from 77 to 85 percent and generally occurred at a fuel-air ratio of about 0.025.

The net thrust (fig. 13) reflects trends of exhaust-gas temperature and the specific fuel consumption reflects trends of exhaust-gas temperature and combustion efficiency. At an altitude of 30,000 feet and limiting turbine-outlet temperature (1760° R), type 4 configuration had a specific fuel consumption of 2.2 at a fuel-air ratio of 0.035, whereas at the peak turbine-outlet temperature of 1660° R, type 1 configuration had a specific fuel consumption of 3.7 at a fuel-air ratio of 0.07. In general, at a given tail-pipe-burner fuel-air ratio, the net thrust was higher and the specific fuel consumption was lower for configuration types 4 and 5 at all altitudes and the margin between these types and configuration types 1, 2, and 3 became increasingly greater as altitude was increased.

The relative performance of the five configuration types is illustrated in terms of net thrust and specific fuel consumption in figure 14 for an altitude of 30,000 feet. The data indicated that for a given net thrust, configuration types 4 and 5 operated with lower specific fuel consumption than configuration types 1, 2, and 3. Therefore on the basis of high altitude operational limits and best performance, configuration type 4 and type 5 were the best investigated for this particular burner geometry. The burner performance was improved by the same combined factors that improved the altitude limits, namely: (1) radial fuel injection with uniform distribution over the flame holder, (2) increased fuel mixing length, and (3) a V-gutter flame holder.

Operational Characteristics

The tail-pipe-burner losses presented as $(P_5-P_7)/P_5$ in figure 15 indicate a trend of decreasing pressure-loss ratio with a decrease in blocked area for all configurations. The pressure-loss ratio for the two best configuration types, 4 and 5, was in each case lower than or equal to that of the other configuration types. The pressure-loss ratio remained approximately constant with increasing fuel-air ratio and altitude. Although the pressure-loss ratio remained constant, the actual drop in pressure across the tail-pipe burner increased with increasing fuel-air ratio and turbine-outlet total pressure. The combination of ejector and nozzle losses caused a decrease in thrust of about 1.5 percent as shown in figure 16.

For this particular tail-pipe-burner installation, the over-all dimensions were fixed; consequently, to conserve tail-pipe length, the burner-inlet diffuser was relatively short. In figure 17, the velocity profiles at the diffuser inlet (station 5) and outlet (station 6) show a high velocity gradient near the outer walls and a separation from the inner cone at the inlet with a substantial growth of the boundary layer along the inner cone. It was found during the investigation that this separation along the inner cone and the exhaust-gas swirl and attendant flow separation from the lee side of the long support struts for the inner cone provided regions where burning occurred when fuel was injected near the leading edge of the struts. When fuel was injected near the inner cone and between the trailing edge of the struts and the diffuser outlet, burning took place in the region of separation from the inner cone. Therefore, the separation from both the inner cone and support struts dictated the maximum distance upstream of the diffuser outlet that the fuel injectors could be placed to increase the fuel mixing length. To increase the mixing length beyond these limits would require shortening the diffuser support struts in addition to redesigning the diffuser to prevent flow separation.

In obtaining performance data for the investigation, operation of the nozzle eyelids was not required, consequently they were secured in the open position. With the exhaust nozzle in the open position, the lowered temperatures and pressures in the tail pipe imposed more severe starting conditions on the burner than are normally encountered with the nozzle closed. The two spark plugs which were provided with each of the commercially manufactured configurations usually permitted starts up to an altitude of 30,000 feet. The hot-streak ignition technique, which was used in each of the NACA configurations, permitted starts at all altitudes up to 45,000 feet, which was the maximum altitude at which starts were attempted.

After about 70 hours of operation, the tail-pipe-burner shell was in good condition except for a few minor wrinkles. Considerable difficulty was experienced with the operation of the two-position variable-area exhaust nozzle because of warping and binding of the eyelids, which was probably due to misalinement or maladjustment of the actuator and actuating linkages.

A number of flame holders failed structurally during the investigation because of burning upstream of the flame holder and because of poor fuel distribution. Examples of failures are shown in figures 18 to 21. Typical failures of the H-gutter and the trailing V-gutter are shown in figures 18 and 19. Usually, failures which occurred at an intersection of the V-gutters did not appear to be a fault of the weld, inasmuch as the welds were usually in good condition as shown in figure 20. In figure 21, the intense burning in the sheltered region of

2176

the V-gutter is evident by the burning out of the reinforcing tubing near the leading edge of the gutter. The V-gutter failures could usually be prevented by: (1) increasing the diameter of the flame-holder inner annular V-gutter (if it were in the region of burning off the inner cone), and (2) constructing the flame holders of heavier gage materials.

During the investigation of the configurations which used the radial fuel injectors, considerable trouble was experienced with coking of the fuel-injector tubes. Radiation from the flame holder may have aggravated coking; locating the fuel injectors upstream might alleviate coking. No definite information was obtained as to the cause of this coking, but in the use of internal fuel manifolds (basic configuration types 1, 2, and 3) there were no coking problems. These manifolds had no dead ends in the flow passages which may have been the starting place for coking.

SUMMARY OF RESULTS

In an investigation of a J35-A-21 turbojet engine with a short converging conical tail-pipe burner having a two-position exhaust nozzle, a number of flame-holder and fuel-system configurations were evaluated at rated engine speed and at a constant flight Mach number of 0.6 for a range of altitudes and tail-pipe-burner fuel-air ratios. The following results were obtained:

1. The performance characteristics and altitude operating limits of the tail-pipe burner were improved by the combined effects of (1) radial fuel injection with uniform distribution over the flame holder, (2) increased fuel mixing length, and (3) a V-gutter-type flame holder.

2. A maximum altitude limit of about 58,000 feet was obtained with a V-gutter flame holder. In most cases the altitude limit with the V-gutter flame holders was about 50,000 feet, and combustion efficiency, exhaust-gas temperature, and specific fuel consumption were only slightly affected by changes in altitude up to 40,000 feet.

3. The maximum altitude limits of the H-gutter and the H-gutter with a trailing V-gutter flame holder were 40,000 and 44,000 feet, respectively. With these configurations, the combustion efficiency and exhaust-gas temperature decreased and the specific fuel consumption increased rapidly with an increase in altitude.

4. The short tail-pipe-burner inlet diffuser had a high velocity gradient near the outer wall and separation existed at the inlet on the

[redacted]

inner cone with a substantial growth of the boundary layer along the inner cone.

2176

5. With the two-position exhaust nozzle open, starting by spark plug ignition was limited to altitudes up to 30,000 feet, whereas starts with the hot-streak ignition technique were obtained at all altitudes up to 45,000 feet, which was the maximum altitude at which starts were attempted.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

APPENDIX - METHODS OF CALCULATION

Symbols

The following symbols are used in this report:

A	area, sq ft 2176
C_d	flow (discharge) coefficient, ratio of effective flow area to measured area
C_T	thermal expansion ratio, ratio of hot exhaust-nozzle-outlet area to cold exhaust-nozzle-outlet area
F	thrust, lb
f/a	fuel-air ratio
g	acceleration due to gravity, 32.2 ft/sec^2
H	total enthalpy, Btu/lb
h_c	lower heating value of fuel, Btu/lb
M	Mach number
P	total pressure, lb/sq ft absolute
p	static pressure, lb/sq ft absolute
R	gas constant, 53.3 ft-lb/(lb)($^\circ$R)
T	total temperature, $^\circ$R
T_r	reference temperature, 540° R
V	velocity, ft/sec
W_a	air flow, lb/sec
W_f	fuel flow, lb/hr
W_g	gas flow, lb/sec
γ	ratio of specific heats
η	combustion efficiency

Subscripts:

a air

c calculated

e engine

j jet

n net

s seal

t tail pipe

ua unburned air

0 free-stream ambient condition

1 engine inlet

3 compressor outlet

5 turbine outlet or diffuser inlet

6 tail-pipe-burner inlet

7 exhaust-nozzle inlet, 5 inches forward of throat

8 exhaust-nozzle throat

Methods of Calculation

Flight speed and Mach number. - The simulated flight speed and Mach number at which the engine and tail-pipe burner were operated were determined from the equations

$$V_0 = \sqrt{2gR \frac{\gamma_1}{\gamma_1 - 1} T_1 \left[1 - \left(\frac{p_0}{P_1}\right)^{\frac{\gamma_1 - 1}{\gamma_1}}\right]} \tag{1}$$

$$M_0 = \sqrt{\frac{2}{\gamma_1-1}\left[\left(\frac{P_1}{p_0}\right)^{\frac{\gamma_1-1}{\gamma_1}} - 1\right]} \tag{2}$$

where γ was assumed to be 1.4.

2176

<u>Gas flow.</u> - The compressor-inlet air flow was computed as

$$W_{a,1} = \frac{A_1 p_1}{\sqrt{RT_1}}\sqrt{2g\,\frac{\gamma_1}{\gamma_1-1}\left[\left(\frac{P_1}{p_1}\right)^{\frac{\gamma_1-1}{\gamma_1}} - 1\right]\left(\frac{P_1}{p_1}\right)^{\frac{\gamma_1-1}{\gamma_1}}} \tag{3}$$

where γ was assumed to be 1.4 and the total temperature was assumed to be equal to the indicated temperature inasmuch as the thermocouple recovery factor was 0.96. The engine air flow at station 3 was calculated by subtracting the midframe leakage and the air flow required to drive the tail-pipe-burner fuel pump from the compressor-inlet air flow. The midframe air leakage and tail-pipe-burner fuel-pump air flow were calculated in a similar manner to the compressor-inlet air flow. The total gas flow at the turbine outlet was calculated as

$$W_{g,5} = W_{a,3} + \frac{W_{f,e}}{3600} \tag{4}$$

The total gas flow at the exhaust-nozzle throat was computed as

$$W_{g,8} = W_{g,5} + \frac{W_{f,t}}{3600} \tag{5}$$

<u>Turbine-outlet temperature.</u> - The turbine-outlet temperature T_5 was the measured average of 30 thermocouples. Due to questionable radiation effect on T_5, a calculated turbine-outlet temperature $T_{5,c}$ was obtained by

$$H_5 = \left(\frac{f}{a}\right)_e\left[\eta_e\, h_c + \lambda\Big|_{T_r}^{5}\right] + H_{a,1} \tag{6}$$

The value of $T_{5,c}$ was then obtained from H_5 and enthalpy charts. A value of 0.96 was selected for the engine combustion efficiency η_e from an altitude calibration of a similar engine. The term λ accounts for the difference between the enthalpy of the carbon dioxide and water

2176

vapor in the burned mixture and the enthalpy of the oxygen removed from the air by their formation (reference 2). Comparison of these turbine-outlet temperatures can be made in table III.

Tail-pipe-burner inlet velocity. - The tail-pipe-burner inlet velocity was calculated by use of the continuity equation. The static pressure and area were measured at station 6. The total pressure and temperature measurements from station 5 were used assuming no loss between the two stations.

$$V_6 = \frac{W_g \; RT_{5,c}}{A_6 \; p_6} \left(\frac{p_6}{P_5}\right)^{\frac{\gamma_6 - 1}{\gamma_6}} \tag{7}$$

The gas flow at station 6 was $W_{g,5}$ or $W_{g,8}$ dependent on the configuration inasmuch as in some configurations the tail-pipe-burner fuel was introduced upstream of station 6 and in others it was introduced downstream of station 6.

Tail-pipe-burner fuel-air ratio. - Two tail-pipe-burner fuel-air ratios are used in this report and are defined as follows:

(1) The ratio of the tail-pipe-burner fuel flow to engine-air flow,

$$\left(\frac{f}{a}\right)_t = \frac{W_{f,t}}{3600 \; W_{a,3}} \tag{8}$$

(2) The ratio of the tail-pipe-burner fuel flow to the unburned air entering the tail-pipe burner,

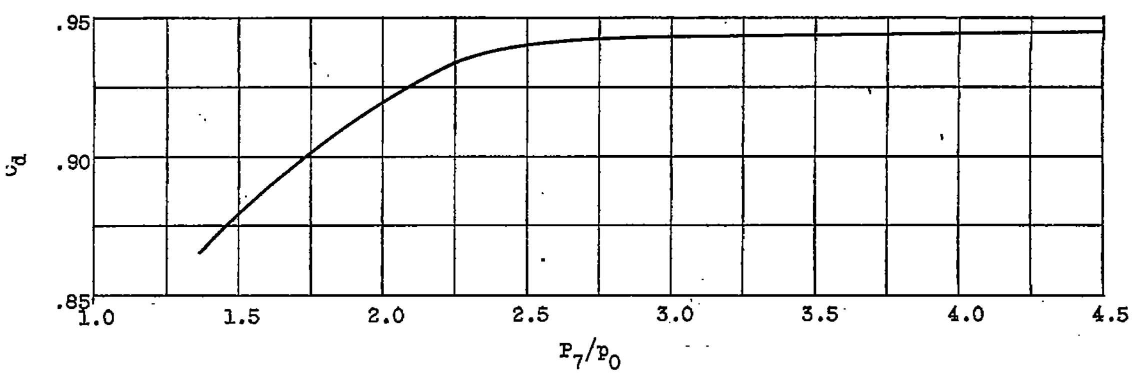
$$\left(\frac{f}{a}\right)_{ua} = \frac{W_{f,t}}{3600 \; W_{a,3} - \frac{W_{f,e}}{0.0667}} \tag{9}$$

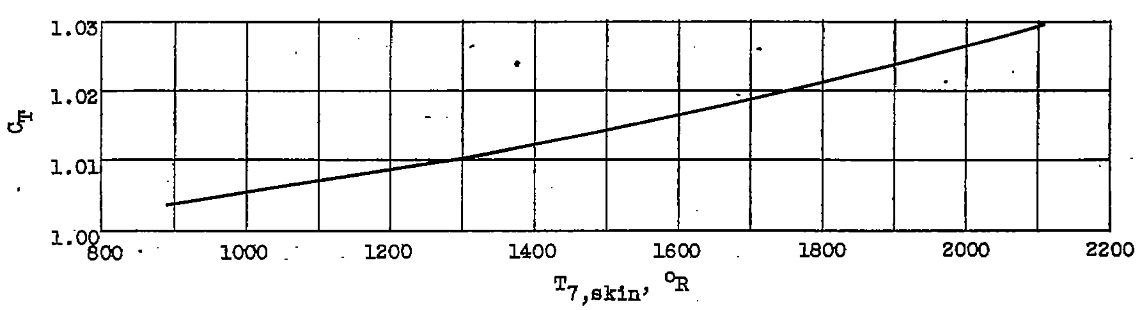
The assumption used in obtaining this equation was that the fuel injected in the engine was completely burned. The value of 0.0667 is the stoichiometric fuel-air ratio for the fuel used.

Exhaust-gas temperature. - The exhaust-gas temperature was determined by

$$T_8 = \left(\frac{A_8\ C_d\ C_T\ p_8}{W_{g,8}}\right)^2 \frac{2g}{R} \left(\frac{\gamma_8}{\gamma_8 - 1}\right)\left[\left(\frac{P_7}{p_8}\right)^{\frac{\gamma_8-1}{\gamma_8}} - 1\right]\left(\frac{P_7}{p_8}\right)^{\frac{\gamma_8-1}{\gamma_8}} \qquad (10)$$

The flow coefficient C_d was obtained from reference 3. The exhaust-nozzle throat area A_8 was measured at room temperature. Values of the thermal expansion ratio C_T of the exhaust nozzle were determined from the thermal expansion coefficient for the exhaust-nozzle material and the measured skin temperature.





Exhaust-nozzle-throat static pressure p_8 was determined as follows:

When

$$\frac{P_7}{p_0} < \left(\frac{\gamma_8+1}{2}\right)^{\frac{\gamma_8}{\gamma_8-1}}$$

then

$$p_8 = p_0 \text{ (subsonic flow)}$$

2176 When

$$\frac{P_7}{p_0} \geqq \left(\frac{\gamma_8+1}{2}\right)^{\frac{\gamma_8}{\gamma_8-1}}$$

then

$$p_8 = \frac{P_7}{\left(\frac{\gamma_8+1}{2}\right)^{\frac{\gamma_8}{\gamma_8-1}}} \text{ (sonic flow)}$$

The nozzle-throat total pressure was assumed equal to the total pressure measured at station 7 (5 in. upstream of the throat). The values of γ_8 were obtained from charts of γ against f/a and T from the first approximation of T_8 which was calculated using the value of $\gamma = 1.24$.

Tail-pipe-burner combustion efficiency. - The tail-pipe-burner combustion efficiency was calculated by the equation

$$\eta_t = \frac{H_a\Big]_1^8 + \left(\frac{f}{a}\right)_e \lambda\Big]_{T_r}^8 + \left(\frac{f}{a}\right)_t \lambda\Big]_{T_r}^8 - \left(\frac{f}{a}\right)_e \eta_e h_c}{h_c\left[\left(\frac{f}{a}\right)_t + \left(\frac{f}{a}\right)_e (1 - \eta_e)\right]} \tag{11}$$

Dissociation was not considered in the calculation of combustion efficiency inasmuch as its effect is negligible for temperatures of up to 3600° R. The engine fuel was not assumed to be burned completely in the engine. The unburned engine fuel was charged to the tail-pipe burner. The engine combustion efficiency was selected to be a value of 0.96 which was obtained from an altitude calibration of this engine type.

Thrust. - The actual jet thrust was calculated by the equation

$$F_j = F_d + A_s (P_1 - p_0) \tag{12}$$

where F_d was obtained from balanced air-pressure diaphragm measurements. Net thrust was obtained from the actual jet thrust by

$$F_n = F_j - \frac{W_{a,1} V_0}{g} \tag{13}$$

2176

The theoretical jet thrust was calculated as

$$F_{j,8} = W_{g,8} \sqrt{\frac{2R}{g} \frac{\gamma_8}{\gamma_8 - 1} T_8 \left[1 - \left(\frac{p_8}{P_7}\right)^{\frac{\gamma_8 - 1}{\gamma_8}}\right]} + A_8 C_T \left[p_8 - p_0\right] \tag{14}$$

The values of p_8, γ_8, and C_T used are explained in the discussion of equation (10).

REFERENCES

1. Fleming, W. A., Conrad, E. William, and Young, A. W.: Experimental Investigation of Tail-Pipe-Burner Design Variables. NACA RM E50K22, 1951.

2. Turner, L. Richard, and Lord, Albert M.: Thermodynamic Charts for the Computation of Combustion and Mixture Temperatures at Constant Pressure. NACA TN 1086, 1946.

3. Grey, Ralph E., Jr., and Wilsted, H. Dean: Performance of Conical Jet Nozzles in Terms of Flow and Velocity Coefficients. NACA Rep. 933, 1949. (Formerly NACA TN 1757.)

[redacted]

TABLE I. - CONFIGURATION DETAILS FOR TAIL-PIPE BURNERS INVESTIGATED ON J35-A-21 TURBOJET ENGINE

Configuration type			Flame holder								Fuel System						Diffuser inner cone
Basic	Specific	Photograph	Gutter: Type	Gutter: Figure	Gutter Holes: Number	Gutter Holes: Diameter (in.)	NACA design	Position	Projected blocked area (percent)	Remarks	Fuel mixing length (in.) (a)	Holes: Number	Holes: Diameter (in.)	NACA Injector: Number	NACA Injector: figure	Remarks	
1	A	4(a)	H	5(a)	200	1/8	---	1	25.5	2 annular gutters Leading edge curved inward	$\frac{1}{8}$ - $\frac{7}{8}$	198	0.025	---	---	3 annular tubes connected by radial tubes, see table II for injection direction	Standard
1	B	4(a)	H	5(b)	732	1/8	---	1	25.5	2 annular gutters Fuel deflector plates, figure 4(a), part 5	7/8	198	.025	---	---		Standard
1	C	4(a)	H	5(b)	732	1/8	---	1	25.5	2 annular gutters Fuel deflector plates, figure 4(a), parts 4 and 5	7/8	243	.025	---	---		Standard
1	D	4(b)	H	5(c)	840	1/8	---	1	30.9	3 annular gutters	$1\frac{5}{8}$	200	.025	---	---		Standard
2	E	4(c)	H-V	5(b)	680	1/8	---	1	37.2	2 annular H-gutters with single trailing V-gutter 6 inches downstream	7/8	239	0.025	---	---	3 annular tubes connected by radial tubes, see table II for injection direction	Standard
2	F	4(c)	H-V	5(b)	732	1/8	---	1	36.2		7/8	243	.025	---	---		Standard
2	G	4(c)	H-V	5(b)	732	1/8	---	1	36.2	2 annular H-gutters with single trailing V-gutter 4 inches downstream	7/8	243	.025	---	---		Standard
2	H	4(e)	H-V	5(d)	637	3/32	---	1	45.3	2 annular H-gutters with single trailing V-gutter 6 inches downstream Leading edge curved inward and trailing edge curved outward	$1\frac{11}{16}$	201	.025	---	---	2 annular tubes with short radial tubes, see table II for injection direction	Standard
2	I	4(f)	H-V	5(e)	732	1/8	---	1	40.6	2 annular H-gutters with 2 trailing V-gutters 6 inches downstream	$1\frac{7}{8}$	328	.020	---	---	3 annular tubes connected by radial tubes Adjacent tubes with 45° impinging jets, see table II	Standard
3	J	4(g)	V	5(f)	---	---	---	1	28.9	2 annular gutters	$8\frac{1}{2}$	229	0.025	---	---	3 annular tubes connected by radial tubes (tubes streamlined) see table II for injection direction	Standard
4	K	----	V	----	---	---	---	1	28.9	Same flame holder used in configuration J	10	192	0.025	1	7(a)	12 radial tubes equally spaced circumferentially injecting fuel normal to gas flow	Modified
4	L	----	V	6(a)	---	---	1	1	31.2	2 annular gutters	$5\frac{5}{8}$	144	.025	2	7(b)		Standard
4	M	----	V	6(b)	---	---	2	1	35.2	Lips on trailing edges	$5\frac{5}{8}$	144	.025	3	7(c)		Standard
4	N	----	V	6(c)	---	---	3	2	32.2	2 annular gutters	3	144	.025	4	7(d)		Standard
4	O	----	V	6(a)	---	---	1	2	30.7	2 annular gutters	3	144	.025	2	7(b)		Standard
5	P	----	V	6(d)	---	---	4	1	26.6	Short radial gutters connected by one annular gutter	$5\frac{5}{8}$	144	0.025	2	7(b)	12 radial tubes equally spaced circumferentially injecting fuel normal to gas flow	Standard

[a]Mixing length is defined as distance from point of fuel injection to leading edge of flame holder.

NACA

TABLE II. - FLAME-HOLDER AND FUEL-SYSTEM PART DETAILS FOR CONFIGURATIONS A THROUGH J

Part	Configuration									
	A	B	C	D	E	F	G	H	I	J
Fuel manifold										
(1) Number of holes	48[a]	48[b]	48[b] 47[d]	64[b]	91[b]	Same as configuration C except has a trailing V-gutter 6 inches downstream	Same as configuration F except has a trailing V-gutter 4 inches downstream	65[b]	72[c]	93[b]
Ring diameter	23.58	23.58	23.58	23.58	24.58			23.58	24.38	23.58
(2) Number of holes	24[a]	24[b]	24[b]	56[b]	24[b]			24[b]	64[c]	28[b]
Ring diameter	11.10	11.10	11.10	15.75	12.10			11.10	22.63	11.10
(3) Number of holes	16[b]	16[b]	16[b]	24[b]	16[b]			24[b]	16[c]	12[b]
Ring diameter	4.58	4.58	4.58	7.86	4.58			-----	11.86	4.58
(4) Number of holes	12[a]	12[b]	12[b]	12[b]	12[b]			32[b]	-----	24[b]
(5) Number of holes	12[b]	12[b]	12[b]	8[b]	12[b]			32[b]	-----	8[b]
(6) Number of holes	12[a]	12[b]	12[b]	4[b]	12[b]			24[b]	32[c]	64[b]
(7) Number of holes	72[b]	72[b]	72[b]	12[b]	72[b]			-----	72[b]	-----
(8) Number of holes				20[b]					40[b]	
(9) Number of holes									24[c]	
Ring diameter									10.19	
(10) Number of holes									8[c]	
Ring diameter									4.58	
Flame holder										
[1] Number of holes	104	364	364	372	314			368	364	-----
Ring diameter	23.35	23.35	23.35	23.35	24.35			23.35	23.35	23.35
[2] Number of holes	48	192	192	256	192			149	192	-----
Ring diameter	11.00	11.00	11.00	15.44	12.00			11.00	11.00	11.00
[3] Number of holes	48	176	176	-----	176			120	176	-----
[4] Deflector plate	None	4	4	None	None			None	None	None
[5] Deflector plate	None	None	4	None	None			None	None	None
[6] Number of holes				120						
Ring diameter				7.75						
[7] Number of holes				64						
[8] Number of holes				32						
[9] Ring diameter					17.18	17.18		17.18	17.18	
[10] Ring diameter									4.5	

NACA

[a] Downstream injection.
[b] Upstream injection 15° from flow direction.
[c] Upstream injection 45° from flow direction.
[d] Upstream injection.

NACA

TABLE III. - PERFORMANCE DATA WITH TAIL-

Run	Altitude (ft)	Tail-pipe-burner fuel consumption $W_{f,t}$ (lb/hr)	Engine fuel consumption $W_{f,e}$ (lb/hr)	Jet thrust F_j (lb)	Net thrust F_n (lb)	Air consumption W_a (lb/sec)	Specific fuel consumption W_f/F_n (lb/lb thrust)	Tail-pipe burner fuel-air ratio $(f/a)_t$	Tail-pipe-burner fuel-air ratio $(f/a)_{ua}$	Tail-pipe burner inlet velocity V_5 (ft/sec)	Tail-pipe-outlet total temperature T_8 (°R)
					CONFIGURATION A						
1	10,000	2400	3172	4293	2706	75.72	2.059	0.0088	0.0107	390.7	1731
2		4820	4159	5856	4291	75.72	2.093	.0177	.0229	382.6	2410
3		7070	4525	6556	4993	75.39	2.322	.0260	.0347	372.7	2746
4		9465	4805	6838	5270	75.80	2.708	.0347	.0471	374.9	2854
5		9510	4701	6678	5143	74.77	2.763	.0353	.0479	375.3	2808
6	30,000	2605	1930	2745	2049	36.54	2.213	0.0198	0.0254	378.0	2167
7		3050	2040	2867	2160	36.24	2.356	.0234	.0305	380.4	2273
8		3255	2063	2924	2240	36.58	2.374	.0247	.0323	376.6	2294
9		3960	2088	2905	2201	36.26	2.748	.0303	.0399	379.8	
10		3985	2088	2924	2246	36.04	2.704	.0307	.0405	379.5	2348
					CONFIGURATION B						
11	10,000	2088	3183	4026	2514	75.69	2.087	0.0077	0.00929	402.8	1633
12		3865	3885	5227	3687	75.29	2.102	.0143	.01816	391.6	2172
13		6615	4562	6309	4760	75.20	2.348	.0244	.03269	385.2	2649
14		9945	4894	6655	5125	75.16	2.895	.0368	.05043	386.0	2808
15		13290	4904	6755	5223	74.79	3.483	.0494	.06780	383.8	2792
16	30,000	2300	1885	2504	1835	35.59	2.281	0.0180	0.02303	385.3	2091
17		3730	2111	2853	2185	35.62	2.675	.0291	.03862	383.3	2380
18		4922	2183	2982	2321	35.45	3.061	.0386	.05187	379.0	2508
19		6495	2264	3065	2392	35.57	3.662	.0507	.06901	380.8	2508
20		8350	2190	2931	2270	35.79	4.643	.0648	.08696	381.6	2324
21	40,000	4060	872	954	519	22.77	9.503	0.0495	0.05893	427.1	1057
22		4880	877	943	528	22.74	10.90	.0596	.07101	429.8	1062
23		5755	881	938	536	23.09	12.38	.0692	.08231	424.6	995
24		7185	861	959	538	22.83	14.96	.0874	.1037	437.4	1008
					CONFIGURATION C						
25	10,000	2365	3245	4205	2687	74.43	2.088	0.0088	0.0108	402.3	1737
26		2380	3209								
27		3195	3535	4647	3136	74.15	2.148	.0120	.0149	395.2	1946
28		5005	4131								
29		6725	4618	6351	4838	74.79	2.345	.0250	.0336	389.7	2672
30		9005	5022	6891	5379	73.77	2.608	.0339	.0473	392.9	3004
31	30,000	2710	2025	2772	2089	36.97	2.267	0.0204	0.0264	383.9	2126
32		3460	2215	3091	2420	37.31	2.345	.0258	.0342	381.7	2358
33		3925	2279	3136	2471	36.32	2.511	.0300	.0406	383.7	2519
34		4400	2320	3175	2504	37.26	2.684	.0328	.0443	383.2	2434
35		4420	2295	3138	2447	37.09	2.744	.0331	.0446	387.0	2419
36		6180	2360	3264	2585	36.86	3.304	.0466	.0635	382.0	2486
					CONFIGURATION D						
37	10,000	2005	3165	4054	2516	74.11	2.065	0.0075	0.0091	398.6	1679
38		4180	3960	5265	3736	73.87	2.179	.0157	.0202	392.4	2237
39		6725	4516	6157	4643	73.57	2.421	.0254	.0341	385.6	2656
40		9730	4758	6440	4940	74.21	2.933	.0364	.0497	384.4	2726
41		12860	4825	6495	4965	74.90	3.562	.0477	.0652	387.0	2662
42	30,000	2330	1900	2532	1816	34.99	2.285	0.0185	0.0239	389.6	2124
43		3310	2072	2816	2129	35.99	2.528	.0256	.0336	383.5	2270
44		4520	2230	2962	2295	36.25	2.941	.0346	.0466	388.1	2353
45		5730	2295			35.64		.0447	.0610	386.6	
46		6830	2254	3033	2376	35.06	3.823	.0541	.0739	382.9	2484
47	35,000	2430	1640	2150	1642	28.65	2.479	0.0236	0.0309	388.3	2181
48		2980	1693	2244	1719	28.83	2.718	.0287	.0380	388.2	2212
49		3770	1717	2295	1789	28.36	3.067	.0369	.0494	383.8	2357
50		4640	1832	2422	1902	29.06	3.403	.0444	.0601	387.2	2351
51		4925	1815			28.37		.0482	.0657	388.8	
					CONFIGURATION E						
52	30,000	2200	1870	2506	1858	35.07	2.191	0.0174	0.0224	385.2	2087
53		2230	1908	2577	1892	35.38	2.187	.0175	.0226	389.8	2110
54		2250	1908	2505	1848	34.72	2.250	.0180	.0233	390.3	2156
55		3160	2088	2841	2178	35.14	2.410	.0250	.0332	384.9	2383
56		4120	2361	3190	2522	34.63	2.570	.0330	.0461	381.1	2768
57		4120	2369	3242	2547	34.99	2.548	.0327	.0456	384.2	2742
58		5125	2361	3197	2539	34.99	2.948	.0407	.0566	380.9	2713
59		6115	2451			34.71		.0489	.0693	385.1	
60		6505	2410	3242	2602	34.62	3.426	.0522	.0735	380.2	2782
61		6507	2393	3249	2586	35.01	3.442	.0516	.0722	381.9	2707
62		7207	2377	3249	2582	35.15	3.712	.0570	.0793	380.6	2684
63		7210	2361	3210	2543	35.22	3.764	.0569	.0789	381.0	2614
64	35,000	2315	1655	2220	1684	29.01	2.357	0.0222	0.0291	389.7	2180
65		4540	1962	2646	2116	28.97	3.073	.0435	.0806	383.4	2629
66		7208	1922	2585	2066	28.68	4.419	.0698	.0968	384.0	2483
67	40,000	2640	1305	1758	1340	22.26	2.944	0.0329	0.0438	389.4	2238
68		3405	1482	1990	1568	22.54	3.117	.0420	.0578	388.1	2493
69		4160	1475	1967	1551	22.25	3.633	.0519	.0717	388.4	2477
70		4920	1504	2039	1620	22.29	3.965	.0613	.0853	385.3	2585
71		5000	1557	2041	1621	22.35	4.045	.0621	.0875	392.6	2567
72		6120	1423	1859	1441	22.29	5.235	.0763	.1039	390.9	2258
					CONFIGURATION F						
73	30,000	2500	1978	2864	1248	35.49	3.588	0.0196	0.0255	386.4	2220
74		3349	2110	2846	1457	35.62	3.747	.0261	.0347	386.7	2340
75		4280	2175	2967	1597	35.13	4.042	.0338	.0456	381.9	2525
76		5435	2304	3100	1724	35.41	4.489	.0426	.0585	384.3	2565

2176

2176

PIPE BURNING AT FLIGHT MACH NUMBER OF 0.6

Tail-pipe-burner combustion efficiency η_t	Engine-inlet total pressure P_1 (lb/sq ft)	Turbine-outlet total pressure P_5 (lb/sq ft)	Tail-pipe-burner inlet static pressure p_6 (lb/sq ft)	Tail-pipe-burner outlet total pressure P_7 (lb/sq ft)	Exhaust static pressure p_0 (lb/sq ft)	Engine-inlet total temperature T_1 (°R)	Manufacturer's control temperature T_6 (°R)	Turbine-outlet total temperature T_5 (°R)	Calculated turbine-outlet total temperature $T_{5,c}$ (°R)	Run
CONFIGURATION A										
0.6534	1845	2819	2547	2702	1431	502	1337	1352	1334	1
.7600	1838	3338	3096	3193	1439	505	1560	1561	1575	2
.7119		3577	3343	3412	1440	505	1678	1673	1662	3
.5888	1849	3692	3453	3529	1446	507	1706	1718	1717	4
.5604		3624	3392	3456	1440	501	1697	1702	1711	5
0.5661	802.8	1529	1415	1460	628.9	429	1507	1497	1471	6
.5276	806.3	1565	1452	1497	620.4	435	1532	1530	1530	7
.5183	801.4	1591	1475	1512	630.4	416	1573	1561	1527	8
	802.8	1588	1478	1517	620.4	428	1569	1545	1554	9
.4456	802.8	1584	1478	1526	631.2	428	1563	1554	1561	10
CONFIGURATION B										
0.5454	1838	2789	2486	2651	1470	510	1330	1350	1342	11
.7196	1845	3173	2888	3017	1458	510	1491	1525	1515	12
.6781	1849	3537	3247	3346	1453	510	1659	1702	1674	13
.5255	1849	3675	3384	3476	1465	511	1733	1776	1749	14
.4080	1841	3698	3394	3493	1450	510	1750	1785	1754	15
0.5428	795.7	1486	1360	1397	637.3	446	1483	1491	1481	16
.4701	795.7	1592	1472	1509	635.8	442	1583	1612	1589	17
.4154	795.7	1634	1522	1555	636.5	440	1625	1648	1628	18
.3245	797.2	1670	1550	1577	634.9	439	1639	1663	1663	19
.2271	795.7	1628	1518	1540	638.8	437	1609	1637	1619	20
-0.0254	500.7	725.0	627.5	676.3	397.1	432	1189	1190	1202	21
-.0184	500.0	725.0	623.9	684.8	403.3	431	1184	1188	1206	22
-.0272	500.7	733.6	638.0	683.6	415.9	429	1183	1194	1197	23
-.0152	498.6	702.3	606.3	684.5	402.5	428	1183	1194	1187	24
CONFIGURATION C										
0.5916	1845	2816	2527	2689	1460	522	1353	1380	1381	25
	1849					515	1366			26
.6324	1849	2973	2686	2822	1456	514	1398	1476	1446	27
	1852						1551			28
.6661	1849	3536	3232	3342	1464	514	1691	1753	1696	29
.6398	1845	3718	3552	3519	1458	520	1775	1842	1805	30
0.5130	800.0	1548	1417	1463	626.3	408	1494	1534	1479	31
.5221	799.3	1648	1519	1564	635.6	405	1585	1623	1559	32
.5183	801.4	1663	1534	1583	634.0	418	1572	1657	1626	33
.4438	797.2	1688	1558	1599	633.3	404	1633	1674	1609	34
.4344	795.7	1674	1531	1587	623.0	411	1629	1658	1606	35
.3438	795.7	1706	1582	1617	625.5	410	1658	1688	1643	36
CONFIGURATION D										
0.6010	1848	2791	2508	2634	1448	520	1322	1379	1365	37
.6828	1851	3188	2925	3012	1458	523	1531	1557	1562	38
.6472	1849	3484	3228	3278	1460	523	1684	1718	1697	39
.4947	1849	3594	3348	3380	1469	522	1748	1782	1738	40
.3732	1849	3624	3367	3406	1461	518	1730	1771	1743	41
0.5336	799.3	1469	1349	1383	624.3	452	1535	1559	1510	42
.4743	802.1	1570	1451	1481	628.3	437	1584	1601	1551	43
.3800	799.3	1630	1510	1536	641.5	436	1645	1641	1621	44
	799.3	1649	1538	1559		436	1684	1698	1670	45
.2923	797.2	1638	1527	1543	625.6	436	1672	1678	1669	46
0.4582	633.1	1222	1127	1154	508.1	422	1544	1558	1534	47
.3934	633.8	1249	1155	1176	499.7	422	1567	1582	1560	48
.3739	633.8	1263	1176	1206	505.9	422	1594	1606	1593	49
.3066	633.8	1314	1226	1241	508.9	420	1649	1665	1635	50
	633.8	1297	1208	1227		422	1629	1647	1654	51
CONFIGURATION E										
0.5511	796.5	1465	1342	1383	635.2	442	1483	1490	1485	52
.5552	800.7	1477	1352	1397	628.1	448	1497	1515	1502	53
.5675	799.3	1465	1344	1387	629.8	447	1487	1502	1521	54
.5332	801.4	1563	1449	1483	631.3	445	1588	1597	1596	55
.5591	799.3	1688	1576	1587	622.4	445	1725	1722	1744	56
.5486	801.4	1689	1579	1595	621.5	451	1729	1731	1743	57
.4505	799.3	1691	1582	1600	633.2	445	1723	1724	1731	58
	801.4	1716	1604	1622		443	1746	1746	1787	59
.3856	800.7	1703	1600	1618	633.5	439	1728	1725	1764	60
.3650	801.4	1705	1599	1611	634.3	449	1742	1740	1753	61
.3354	800.7	1709	1596	1618	632.5	446	1729	1726	1737	62
.3160	797.2	1687	1589	1597	630.6	443	1726	1728	1724	63
0.4857	633.8	1226	1132	1167	499.8	417	1513	1531	1529	64
.3981	637.3	1380	1290	1308	503.7	417	1694	1694	1715	85
.2407	633.8	1355	1269	1280	506.4	417	1681	1682	1705	86
0.3601	500.7	968.4	889.4	918.7	395.4	430	1551	1576	1567	67
.3605	500.7	1051	975.7	989.2	396.2	430	1678	1695	1691	68
.2974	500.7	1037	970.4	983.3	396.2	428	1667	1681	1701	69
.2912	500.7	1066	989.8	1010	396.2	430	1685	1707	1721	70
.2755	500.0	1062	994.0	1010	393.0	424	1698	1704	1754	71
.1791	500.7	1009	942.2	954.5	395.4	427	1619	1642	1658	72
CONFIGURATION F										
0.5717	802.8	1513	1399	1437	641.5	442	1515	1527	1531	73
.4883	799.3	1569	1462	1490	633.4	442	1576	1582	1594	74
.4677	799.3	1618	1499	1541	633.8	443	1606	1613	1639	75
.3612	802.8	1657	1553	1576	633.8	442	1667	1673	1693	76

TABLE III. - PERFORMANCE DATA WITH TAIL-

Run	Altitude (ft)	Tail-pipe-burner fuel consumption $W_{f,t}$ (lb/hr)	Engine fuel consumption $W_{f,e}$ (lb/hr)	Jet thrust F_j (lb)	Net thrust F_n (lb)	Air consumption W_a (lb/sec)	Specific fuel consumption W_f/F_n (lb/lb thrust)	Tail-pipe burner fuel-air ratio $(f/a)_t$	Tail-pipe burner fuel-air ratio $(f/a)_{ua}$	Tail-pipe burner inlet velocity V_6 (ft/sec)	Tail-pipe outlet total temperature T_8 (°R)
CONFIGURATION G											
77	30,000	2250	2079	2767	2105	35.29	2.057	0.0177	0.0235	388.2	2297
78		3290	2335	3073	2420	35.20	2.324	.0260	.0359	386.0	2588
79		4160	2522	3302	2635	35.38	2.536	.0327	.0465	385.6	2771
80		5440	2580	3372	2710	35.50	2.959	.0426	.0610	384.7	2816
CONFIGURATION H											
81	10,000	2040	3085	3797	2258	74.67	2.270	0.0076	0.0092	405.1	1537
82		3105	3673	4787	3245	73.99	2.089	.0117	.0147	390.6	2022
83		4360	4160	5515	3971	74.05	2.146	.0164	.0213	388.2	2350
84		5545	4500	6021	4483	73.78	2.241	.0209	.0280	382.8	2624
85		5545	4590	6146	4576	74.63	2.215	.0206	.0277	385.2	2622
86		6830	4892	6503	4979	73.84	2.354	.0257	.0355	383.7	2849
87		8165	5052	6786	5259	73.92	2.513	.0307	.0429	381.2	2950
88	30,000	2169	2010	2667	2002	35.09	2.087	0.0172	.0225	386.6	2281
89		3480	2271	3011	2352	35.30	2.445	.0274	.0374	382.5	2580
90		5205	2427	3224	2562	34.83	2.979	.0415	.0585	382.6	2790
91		7070	2467	3321	2638	35.67	3.615	.0551	.0773	381.6	2711
92		8345	2427	3262	2572	35.89	4.188	.0646	.0899	383.6	2610
93	40,000	2400	1400	1800	1382	21.89	2.750	0.0305	.0415	395.3	2435
94		3270	1400	1779	1374	22.16	3.399	.0410	.0558	393.3	2363
95		4240	1431	1778	1358	22.20	4.176	.0531	.0725	398.6	2299
96		5105	1371	1722	1297	22.03	4.993	.0644	.0869	395.3	2241
CONFIGURATION I											
97	30,000	2345	1939	2562	1891	34.88	2.265	0.0187	0.0243	491.7	2205
98		2345	1970	2613	1968	34.99	2.193	.0186	.0243	487.5	2260
99		3055	2058	2703	2038	34.66	2.509	.0245	.0325	496.7	2363
100		3785	1970	2550	1877	34.66	3.066	.0303	.0397	492.8	2206
101		4280	1931	2519	1858	34.75	3.343	.0342	.0445	489.4	2159
102		5205	1821	2391	1731	34.69	4.059	.0417	.0533	486.3	1990
CONFIGURATION J											
103	10,000	2710	3563	4615	3098	74.93	2.025	0.0100	0.0125	397.8	1827
104		4080	4059	5330							
105	30,000	2418	2120	2811	2151	35.01	2.110	0.0192	.0257	392.3	2330
106		2980	2200	3044	2377	35.36	2.179	.0234	.0316	379.5	2539
107		3750	2485	3197	2538	35.17	2.457	.0296	.0420	393.3	2741
108		4520	2570	3386	2730	35.53	2.597	.0353	.0506	390.6	2844
109		5330	2690	3483	2831	34.91	2.833	.0424	.0624	393.5	3030
110	40,000	1690	1269	1626	1224	21.97	2.417	0.0214	.0281	404.8	2060
111		2280	1468	1977	1567	21.98	2.392	.0288	.0399	398.4	2546
112		2980	1625	2078	1667	22.09	2.762	.0375	.0540	406.5	2690
113		3730	1679	2184	1769	22.04	3.058	.0470	.0688	406.8	2810
CONFIGURATION K											
114	30,000	1637	1985	2616	1949	36.19	1.858	0.01256	0.0163	394.5	2025
115		2070	2239	2943	2284	36.04	1.887	.01595	.0215	391.8	2403
116		2500	2418	3199	2530	36.00	1.944	.01929	.0268	391.4	2643
117		3120	2564	3354	2678	36.18	2.122	.02395	.0340	391.0	2789
118	40,000	930	1239	1605	1193	22.61	1.818	0.01143	0.0148	406.3	1940
119		1240	1386	1839	1422	22.57	1.847	.01526	.0205	402.0	2266
120		1601	1519	2027	1606	22.54	1.943	.01973	.0274	399.2	2556
121		1990	1609	2117	1696	22.48	2.122	.02459	.0350	397.9	2759
CONFIGURATION L											
122	10,000	2365	3536	4671	3150	75.54	1.873	0.0087	0.0108	395.7	1844
123		2890	3812	5051	3529	75.06	1.899	.0107	.0136	395.5	2054
124		3945	4187	5602	4080	74.90	1.993	.0146	.0191	389.8	2350
125		4720	4397	5909	4374	75.40	2.084	.0174	.0230	390.6	2464
126		7960	5012	6761	5218	75.03	2.486	.0295	.0408	385.7	2901
127	30,000	1419	1770	2333	1657	35.44	1.925	0.01112	0.0140	396.4	1832
128		1558	1886	2624	1960	35.21	1.757	.0123	.0158	384.7	2136
129		2298	2206	2993	2340	35.00	1.925	.01824	.0247	384.9	2597
130		2450	2247	3045	2392	34.97	1.964	.0195	.0266	386.2	2600
131		2978	2377	3210	2544	35.38	2.105	.02338	.0325	386.6	2738
132		3350	2443	3242	2592	34.81	2.235	.0267	.0378	389.3	2835
133		3730	2522	3349	2698	35.04	2.317	.02957	.0422	388.4	2879
134		4320	2532	3393	2726	35.35	2.514	.0339	.0484	387.7	2899
135		4440	2555	3417	2743	35.09	2.550	.03515	.0504	387.7	2951
136		5540	2548	3381	2700	35.01	2.996	.0440	.0631	389.4	2888
137	40,000	1515	1512	2040	1642	22.47	1.843	0.0187	0.0260	394.7	2590
138		2005	1640	2168	1768	22.53	2.062	.0247	.0355	395.6	2817
139		2460	1701	2280	1865	22.65	2.231	.0302	.0439	393.3	2933
140		2620	1678	2249	1840	22.25	2.336	.03271	.0477	393.9	2989
141		2840	1718	2228	1835	22.24	2.484	.0355	.0523	398.6	2972
CONFIGURATION M											
142	30,000	1741	2048	2724	2052	34.62	1.846	0.0140	0.0185	393.9	2295
143		2200	2245	2966	2304	35.26	1.929	.0173	.0236	389.9	2493
144		2620	2410	3134	2477	35.26	2.031	.0206	.0289	394.4	2648
145		3015	2515	3311	2630	35.78	2.103	.0234	.0331	402.4	2747
146		3580	2675	3455	2808	35.35	2.228	.0281	.0411	394.2	3006
147	40,000	1641	1541	2016	1613	22.57	1.973	0.0202	0.0282	397.8	2546
148		1846	1632	2146	1730	22.68	2.007	.0225	.0322	398.4	2756
149		1933	1670	2153	1754	22.71	2.052	.0236	.0340	398.7	2784
150		2005	1663	2157	1751	22.56	2.095	.0247	.0356	398.3	2767

2176

PIPE BURNING AT FLIGHT MACH NUMBER OF 0.6 - CONTINUED

Tail-pipe-burner combustion efficiency η_t	Engine-inlet total pressure P_1 (lb/sq ft)	Turbine-outlet total pressure P_5 (lb/sq ft)	Tail-pipe-burner inlet static pressure p_6 (lb/sq ft)	Tail-pipe-burner outlet total pressure P_7 (lb/sq ft)	Exhaust static pressure p_0 (lb/sq ft)	Engine-inlet total temperature T_1 (°R)	Manufacturer's control temperature T_6 (°R)	Turbine-outlet total temperature T_5 (°R)	Calculated turbine-outlet total temperature $T_{5,c}$ (°R)	Run
CONFIGURATION G										
0.6513	801.4	1577	1431	1487	633.5	439	1546	1552	1585	77
.5866	800.0	1691	1550	1587	634.7	437	1677	1649	1708	78
.5434	800.0	1777	1640	1660	630.8	433	1762	1721	1793	79
.4497	802.1	1807	1668	1693	636.3	432	1771	1779	1814	80
CONFIGURATION H										
0.3696	1856	2733	2444	2555	1464	523	1313	1355	1344	81
.6871	1859	3070	2807	2864	1462	526	1461	1502	1495	82
.7235	1858	3300	3049	3082	1462	528	1580	1619	1611	83
.7448	1858	3479	3230	3244	1462	528	1669	1713	1690	84
.7463	1856	3520	3269	3279	1458	526	1666	1709	1700	85
.7213	1853	3638	3398	3392	1458	526	1747	1778	1780	86
.6603	1856	3741	3493	3482	1463	524	1791	1837	1815	87
0.6551	799.3	1523	1408	1430	632.9	447	1526	1555	1559	88
.5680	800.0	1650	1548	1550	638.4	446	1653	1672	1663	89
.4611	800.7	1712	1615	1611	632.9	446	1725	1739	1777	90
.3462	801.4	1751	1640	1640	635.7	445	1744	1755	1782	91
.2834	803.5	1730	1622	1628	634.5	444	1720	1734	1738	92
0.4386	499.3	998.9	926.0	937.5	395.8	450	1655	1675	1682	93
.3217	501.4	1003	932.4	944.9	402.8	450	1649	1672	1662	94
.2358	500.0	1001	938.7	941.7	400.1	449	1662	1686	1687	95
.1972	500.7	989.2	919.0	929.6	398.2	450	1623	1648	1652	96
CONFIGURATION I										
0.5778	802.8	1489	999.3	1407	630	458	1512	1538	1537	97
.6307	799.3	1512	1010	1430	632	439	1496	1516	1534	98
.5225	800.0	1544	1027	1455	632	458	1566	1589	1607	99
.3717	801.4	1490	1013	1415	630	459	1525	1549	1563	100
.3243	801.4	1485	1003	1411	635	458	1513	1536	1537	101
.2256	799.3	1437	974.6	1364	632	458	1461	1486	1485	102
CONFIGURATION J										
0.5814	1854	3006	2668	2821	1458	508		1436	1438	103
	1856	3265	2943	3077	1460					104
0.6184	801.4	1572	1422	1487	624.7	433		1564	1607	105
.6501	801.4	1673	1508	1572	625.4	433		1638	1635	106
.5806	801.4	1724	1584	1635	625.8	430		1709	1778	107
.5407	800.7	1787	1634	1689	628.9	430		1764	1807	108
.5173	801.4	1810	1670	1723	626.2	436		1821	1889	109
0.5983	501.4	924.6	835.2	879.2	392.1	426		1499	1552	110
.5111	501.4	1047	935.9	985.7	389.6	427		1644	1714	111
.4357	501.4	1083	986.6	1027	391.3	426		1719	1826	112
.3961	500.7	1121	1008	1055	387.1	428		1775	1876	113
CONFIGURATION K										
0.6475	800.0	1489	1363	1420	632.4	422		1525	1495	114
.7807	800.0	1620	1486	1545	637.3	425		1644	1625	115
.7994	800.7	1696	1569	1620	632.4	426		1723	1712	116
.7326	801.4	1766	1640	1680	633.1	430		1798	1778	117
0.5949	502.1	909.6	823.2	868.6	399.3	420		1515	1493	118
.6861	501.4	985.5	897.2	939.3	395.8	419		1620	1609	119
.7127	501.4	1053	959.1	999.8	392.2	420		1711	1711	120
.6855	500.7	1092	1002	1038	392.9	421		1790	1784	121
CONFIGURATION L										
0.7034	1858	3017	2682	2853	1467	508	1477	1435	1426	122
.7831	1858	3147	2808	2983	1462	508	1554	1497	1499	123
.8247	1858	3356	3013	3180	1463	507	1656	1585	1587	124
.7760	1856	3465	3120	3279	1458	506	1718	1640	1630	125
.8734	1859	3763	3428	3586	1455	506	1873	1786	1777	126
0.5507	800.0	1407	1260	1328	629.6	443	1508	1432	1426	127
.8079	801.4	1505	1344	1422	629.8	434	1549	1474	1487	128
.8458	801.4	1643	1487	1557	633.6	437	1691	1614	1654	129
.7863	801.4	1661	1502	1567	635.6	437	1740	1636	1673	130
.7444	800.0	1731	1566	1631	633.6	440	1781	1698	1725	131
.6913	800.7	1736	1580	1638	633.6	441	1847	1730	1780	132
.6474	801.4	1785	1623	1678	636.4	437	1830	1742	1806	133
.5885	800.0	1795	1633	1693	634.7	440	1898	1766	1804	134
.5684	801.4	1800	1640	1696	629.6	441	1869	1787	1825	135
.4626	801.4	1786	1635	1688	628.7	449	1931	1808	1829	136
0.7857	500.0	1068	961.2	1005	400.0	408	1735	1623	1703	137
.7184	501.4	1121	1016	1057	400.0	408	1835	1710	1796	138
.6517	500.7	1158	1051	1089	397.0	411	1881	1759	1840	139
.6338	500.7	1143	1040	1082	396.3	422	1875	1773	1853	140
.5722	501.4	1145	1046	1082	402.0	417	1894	1778	1883	141
CONFIGURATION M										
0.7755	800.7	1552	1396	1446	631.9	465		1633	1605	142
.7737	801.4	1649	1499	1540	637.4	446		1674	1671	143
.7367	802.1	1697	1551	1592	635.5	440		1722	1746	144
.7111	803.5	1766	1576	1646	633.8	439		1782	1776	145
.7254	801.4	1830	1653	1711	638.5	431		1813	1860	146
0.6728	499.3	1110	968.3	998	404.5	426		1719	1737	147
.7360	499.3	1108	1012	1047	396.8	416		1740	1789	148
.7127	499.3	1126	1025	1053	403.8	414		1769	1811	149
.6680	499.3	1128	1023	1044	399.9	420		1782	1821	150

NACA

TABLE III. - PERFORMANCE DATA WITH TAIL-

2176

Run	Altitude (ft)	Tail-pipe-burner fuel consumption $W_{f,t}$ (lb/hr)	Engine fuel consumption $W_{f,e}$ (lb/hr)	Jet thrust F_j (lb)	Net thrust F_n (lb)	Air consumption W_a (lb/sec)	Specific fuel consumption W_f/F_n (lb/lb thrust)	Tail-pipe burner fuel-air ratio $(f/a)_t$	Tail-pipe burner fuel-air ratio $(f/a)_{ua}$	Tail-pipe burner inlet velocity V_6 (ft/sec)	Tail-pipe outlet total temperature T_8 (°R)
CONFIGURATION N											
151	30,000	1810	2024	2705	1998	35.59	1.919	0.0141	0.0185	404.5	2203
152		1895	2072	2720	2023	35.32	1.961	.0149	.0197	401.9	2290
153		2185	2182	2912	2192	35.83	1.992	.0169	.0227	401.2	2402
154		2535	2311	3098	2372	35.87	2.043	.0196	.0268	397.7	2613
155		2800	2427	3218	2513	35.54	2.080	.0219	.0306	402.0	2788
156	40,000	1257	1319	1804	1372	22.71	1.878	0.0164	0.0203	395.7	2246
157		1454	1451	1905	1468	22.64	1.979	.0178	.0243	407.6	2432
158		1678	1533	2055	1618	22.63	1.985	.0206	.0287	405.7	2621
159		1895	1609	2100	1649	22.88	2.125	.0230	.0325	408.5	2707
160		1914	1610	2083	1638	22.65	2.151	.0235	.0333	406.9	2760
161		2070	1640	2115	1682	22.65	2.206	.0254	.0363	408.8	2809
CONFIGURATION O											
162	10,000	2218	3340	4370	2853	76.04	1.948	0.0081	0.0099	405.6	1684
163		3050	3871	5162	3618	76.34	1.913	.0111	.0141	399.7	2051
164		4040	4250	5726	4184	76.02	1.981	.0148	.0192	395.9	2322
165		5020	4575	6144	4583	76.14	2.094	.0183	.0244	395.5	2539
166		5880	4730	6461	4929	75.75	2.153	.0216	.0291	390.3	2686
167		6762	4932	6661	5111	75.68	2.288	.0248	.0341	391.9	2803
168	30,000	1839	2071	2791	2113	35.97	1.850	0.0142	0.0187	396.2	2280
169		2362	2254	2982	2300	35.64	2.007	.0184	.0250	398.0	2527
170		2752	2337	3057	2395	35.13	2.125	.0218	.0301	396.8	2702
171		3179	2484	3309	2638	35.78	2.147	.0247	.0347	397.6	2831
172		3400	2460	3228	2552	35.39	2.296	.0267	.0376	395.2	2828
173	40,000	1280	1356	1930	1512	22.60	1.743	0.0157	0.0210	403.9	2270
174		1648	1490	1985	1571	22.58	1.997	.0203	.0280	400.4	2518
175		1925	1553	2057	1640	23.00	2.121	.0232	.0323	400.7	2589
176		2230	1625	2134	1712	22.77	2.252	.0272	.0387	398.8	2777
177		2480	1700	2226	1809	23.10	2.311	.0298	.0430	401.6	2846
CONFIGURATION P											
178	10,000	1945	3373	4247	2682	76.18	1.983	0.0071	0.0087	403.4	1714
179		2780	3825	5058	3496	76.25	1.889	.0101	.0128	395.2	2056
180		3730	4159	5554	4009	75.44	1.968	.0137	.0178	390.6	2345
181		4724	4480	6014	4480	75.72	2.054	.0173	.0230	388.8	2559
182		5880	4759	6399	4857	75.61	2.190	.0216	.0293	386.5	2770
183	30,000	1461	1900	2554	1853	36.45	1.814	0.0111	0.0142	395.9	2013
184		1960	2128	2830	2154	35.59	1.898	.0153	.0204	391.7	2395
185		2624	2329	3099	2422	35.64	2.045	.0205	.0281	390.6	2679
186		3370	2485	3297	2604	35.84	2.248	.0261	.0367	391.7	2842
187		4150	2614	3431	2765	35.34	2.446	.0326	.0471	387.1	3085
188	40,000	1667	1533	2125	1719	22.85	1.862	0.0203	0.0281	395.8	2643
189		2005	1610	2133	1720	23.15	2.102	.0241	.0339	395.5	2745
190		2400	1678	2194	1761	23.27	2.316	.0286	.0409	393.4	2863
191		2905	1736	2180	1761	23.18	2.635	.0348	.0506	398.6	2914
192		3235	1717	2331	1905	22.98	2.599	.0391	.0568	396.7	2914

2176

PIPE BURNING AT FLIGHT MACH NUMBER OF 0.6 - CONCLUDED

Tail-pipe-burner combustion efficiency η_t	Engine-inlet total pressure P_1 (lb/sq ft)	Turbine-outlet-total pressure P_5 (lb/sq ft)	Tail-pipe-burner inlet static pressure p_6 (lb/sq ft)	Tail-pipe-burner outlet total pressure P_7 (lb/sq ft)	Exhaust static pressure p_0 (lb/sq ft)	Engine-inlet total temperature T_1 (°R)	Manufacturer's control temperature T_6 (°R)	Turbine-outlet total temperature T_5 (°R)	Calculated turbine-outlet total temperature $T_{5,c}$ (°R)	Run
CONFIGURATION N										
0.7266	802.1	1524	1340	1442	615.1	441		1577	1548	151
.7534	802.1	1544	1368	1460	615.1	441		1604	1579	152
.7490	801.4	1607	1420	1517	610.4	440		1663	1615	153
.7879	802.8	1678	1488	1586	611.6	443		1734	1676	154
.8034	802.8	1709	1523	1627	614.7	440		1772	1745	155
0.7166	500.7	985.4	875.3	933.6	385.7	420		1399	1542	156
.7105	500.7	1022	907.7	964.9	384.1	420		1670	1656	157
.7333	501.4	1060	947.1	1003	384.8	420		1731	1718	158
.7030	500.7	1088	974.6	1033	380.2	420		1773	1760	159
.7204	500.7	1088	975.3	1033	379.4	422		1781	1772	160
.6931	501.4	1103	989.4	1044	387.2	421		1799	1797	161
CONFIGURATION O										
0.5636	1856	2909	2506	2726	1471	499		1407	1368	162
.7616	1856	3193	2797	2996	1467	500		1535	1492	163
.7901	1858	3381	2986	3173	1467	501		1620	1581	164
.7869	1858	3536	3140	3321	1457	501		1698	1656	165
.7682	1858	3633	3242	3405	1469	502		1742	1694	166
.7331	1857	3711	3317	3482	1456	502		1779	1742	167
0.7980	801.4	1574	1391	1482	634.5	434		1585	1555	168
.7599	801.4	1641	1470	1549	631.0	440		1687	1661	169
.7573	800.7	1681	1506	1584	634.5	448		1759	1722	170
.7471	801.4	1756	1561	1654	631.7	435		1777	1758	171
.6910	802.1	1736	1567	1634	631.0	445		1797	1768	172
0.6937	500.7	982.5	878.1	929.7	394.4	418		1589	1587	173
.6836	500.0	1047	940.1	982.7	394.4	418		1684	1685	174
.6411	500.7	1083	973.2	1018	397.9	416		1733	1714	175
.6437	501.4	1119	1003	1047	394.4	421		1788	1778	176
.6209	500.7	1138	1030	1075	397.9	416		1825	1808	177
CONFIGURATION P										
0.6651	1857	2874	2577	2754	1461	511	1479	1416	1382	178
.8448	1859	3149	2830	3001	1464	511	1604	1525	1485	179
.8780	1857	3320	3012	3163	1461	510	1704	1614	1575	180
.8559	1858	3479	3173	3317	1470	510	1789	1685	1643	181
.8207	1858	3614	3332	3454	1467	512	1877	1746	1713	182
0.7506	802.8	1478	1327	1409	625	435	1570	1509	1458	183
.8290	802.8	1578	1438	1506	629.4	438	1714	1626	1595	184
.7972	803.5	1674	1541	1600	632.2	440	1828	1726	1697	185
.7160	802.8	1742	1606	1664	625.1	441	1917	1791	1764	186
.6938	800.7	1805	1666	1719	632.5	437	1972	1841	1833	187
0.7730	499.3	1065	975.3	1020	394.7	416	1824	1720	1700	188
.7128	500.7	1104	1013	1054	399.8	414	1877	1780	1740	189
.6661	502.8	1139	1049	1087	394.3	412	1910	1802	1783	190
.5714	500.0	1149	1060	1098	396.3	410	1951	1843	1831	191
.5168	500.0	1149	1060	1093	394.3	422	1964	1854	1838	192

2176

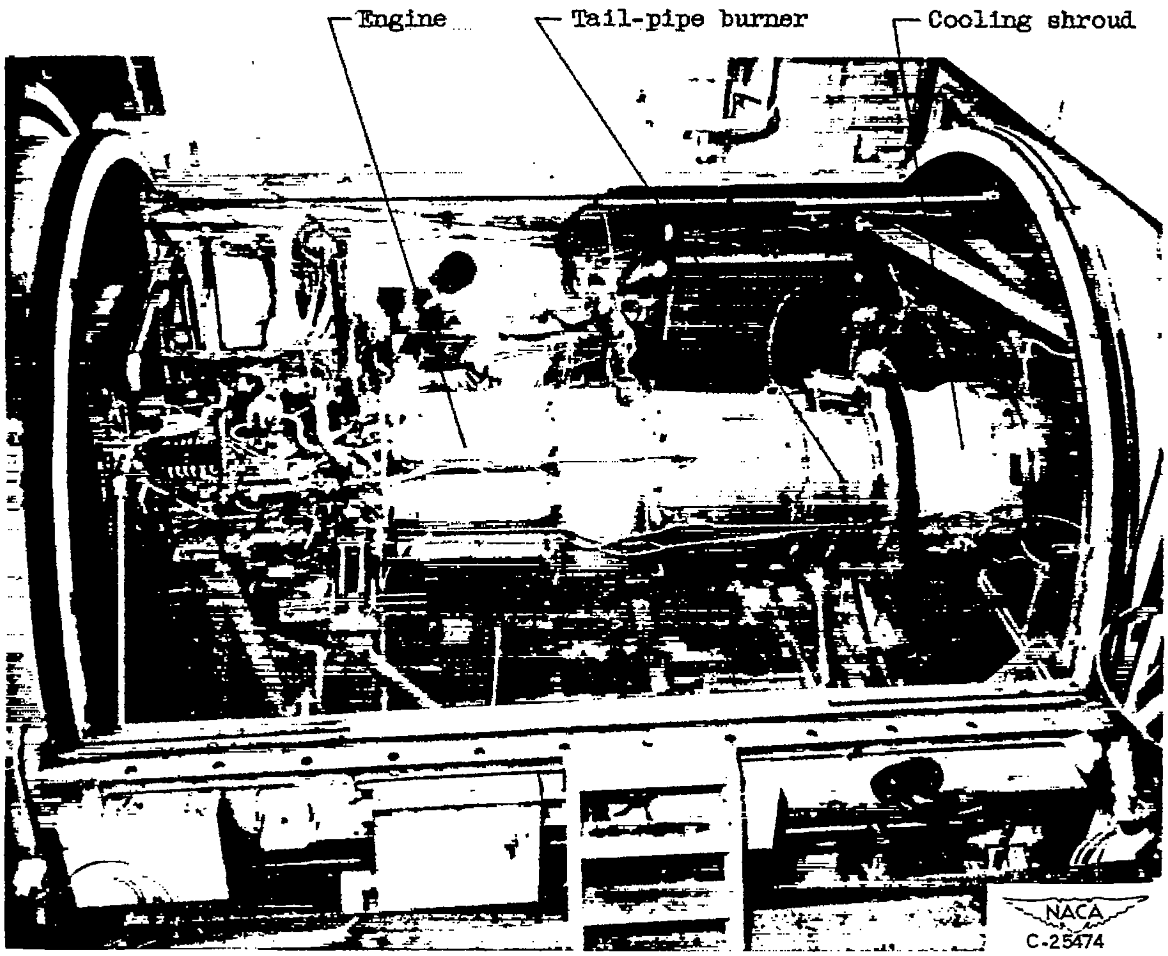


Figure 1. - Installation of engine and tail-pipe-burner assembly in altitude chamber.

[redacted]

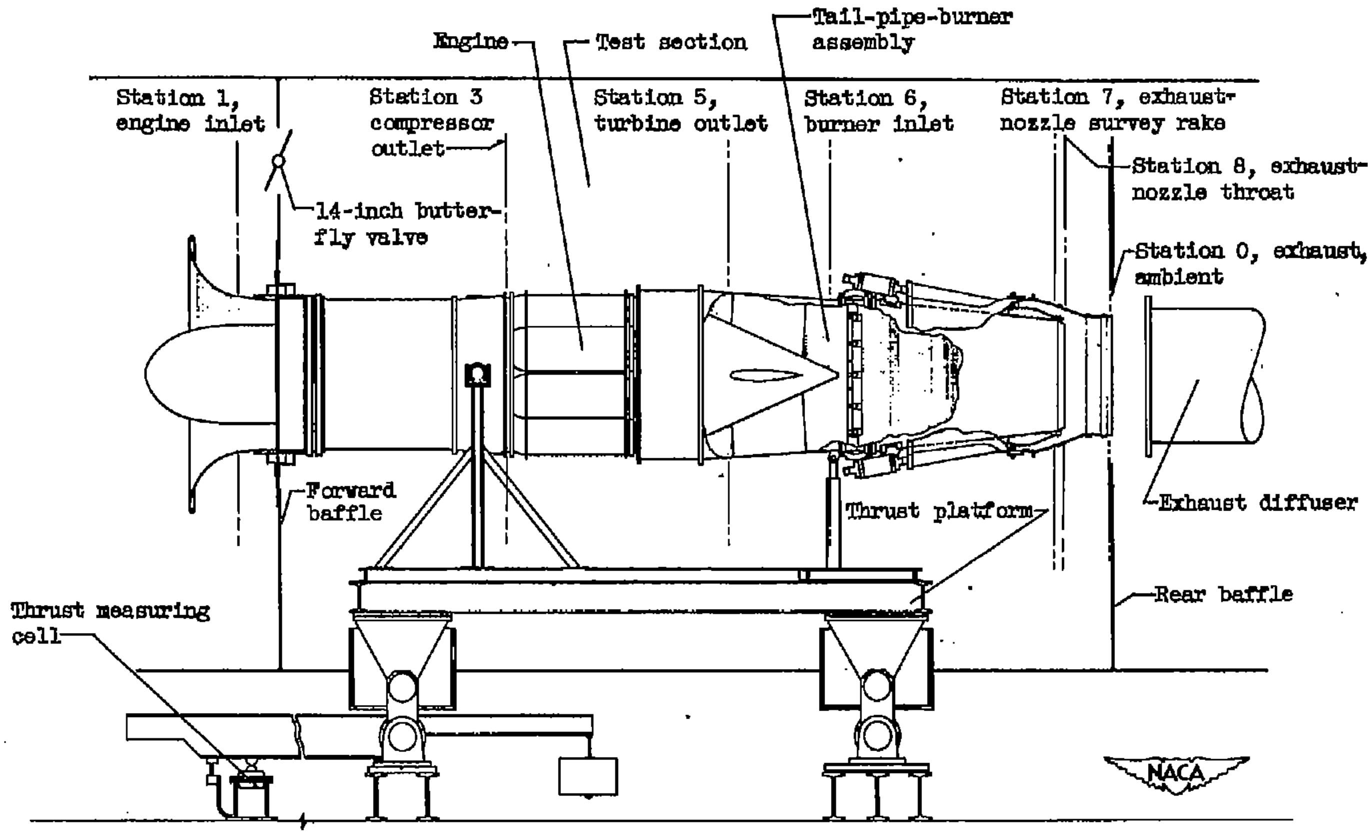
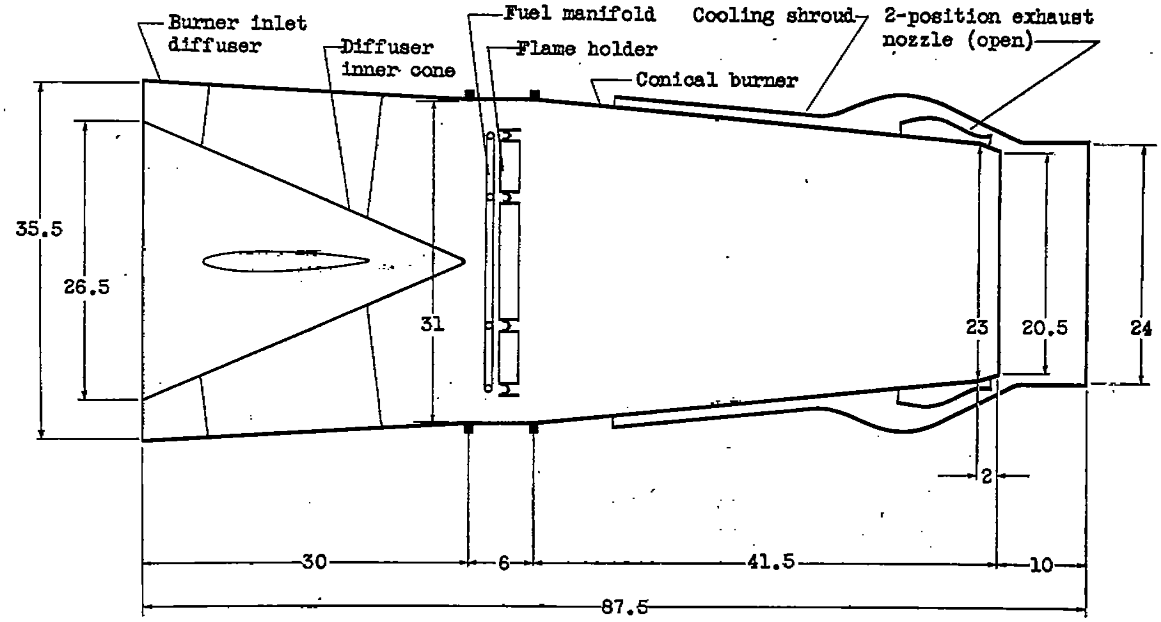


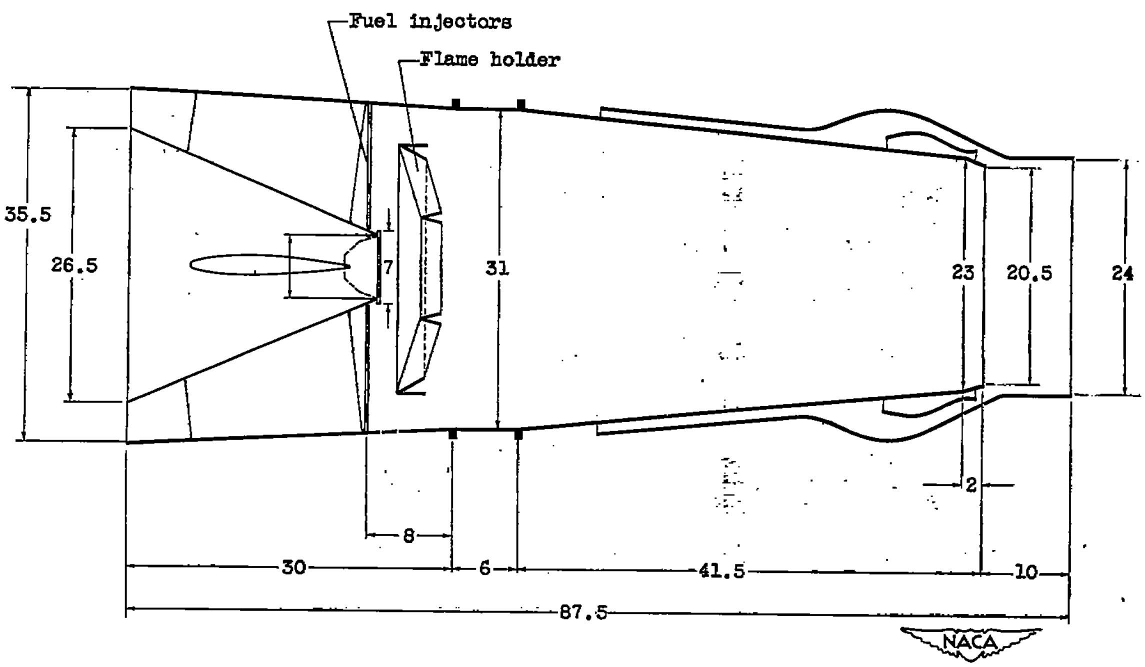
Figure 2. - Schematic drawing of engine and tail-pipe burner in altitude chamber.

[redacted]

2176



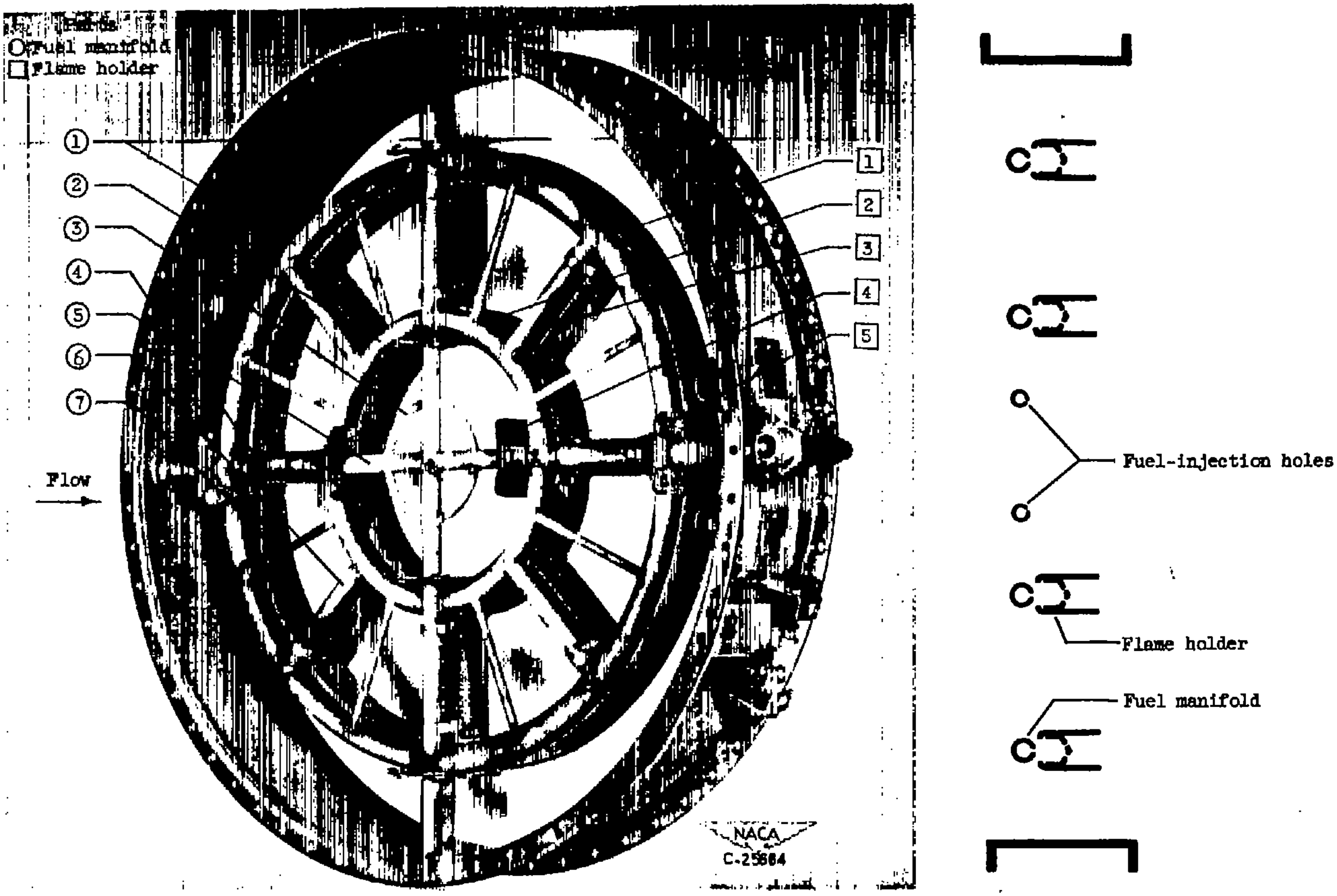
(a) Flame-holder position 1 and standard diffuser inner cone.



(b) Flame-holder position 2 and modified diffuser inner cone.

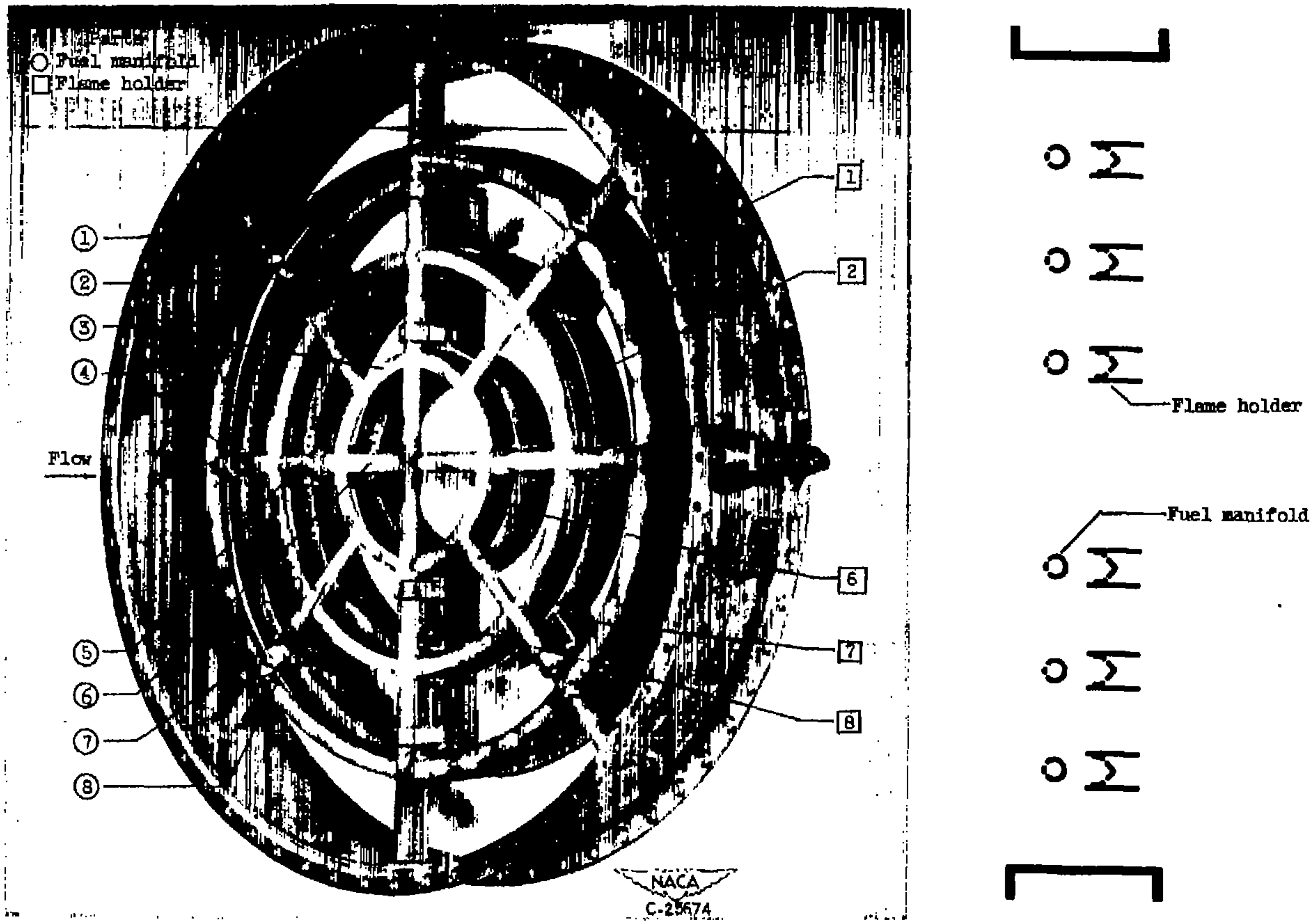
Figure 3. - Schematic drawing of typical tail-pipe-burner assembly.

2153



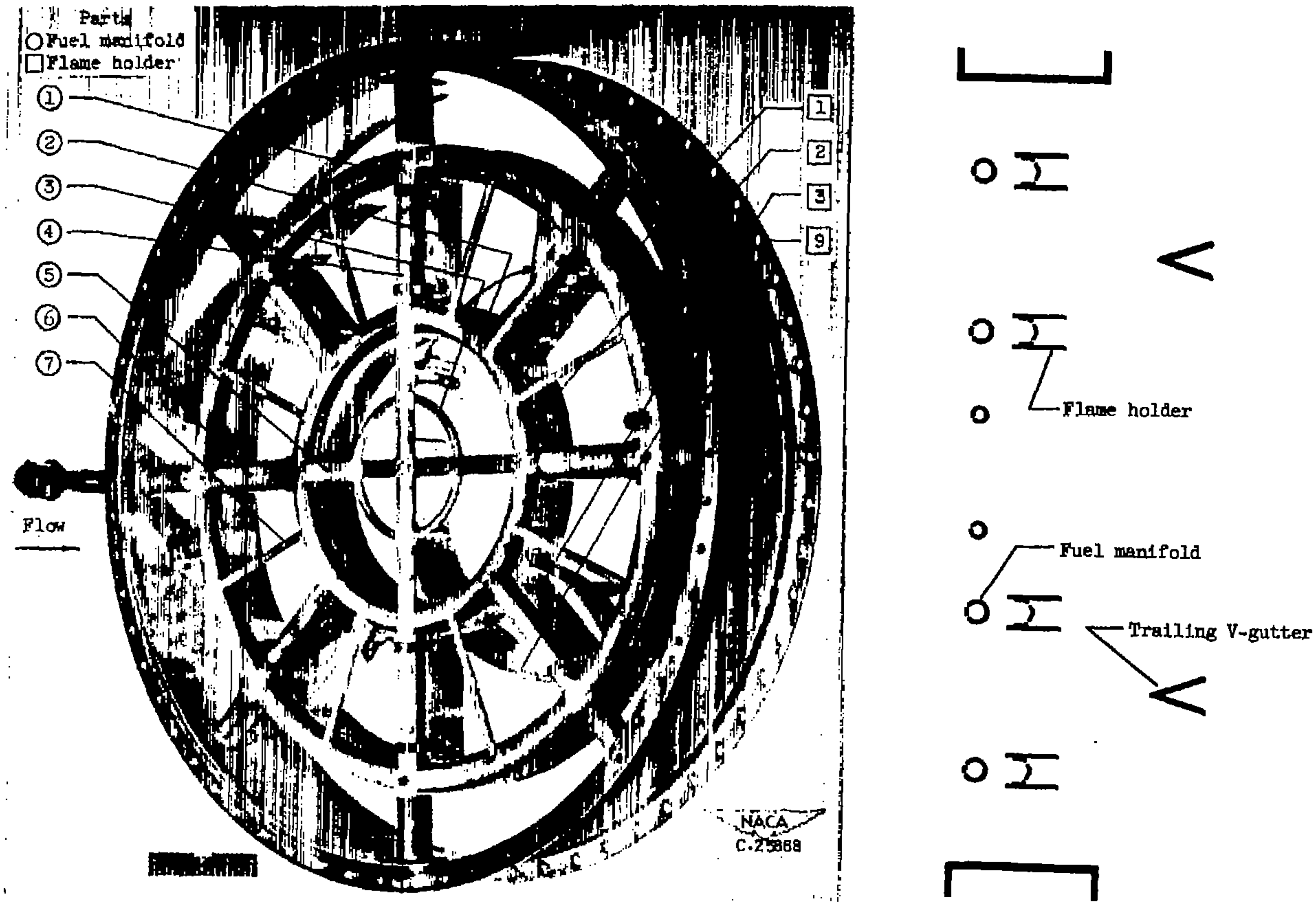
(a) Photograph and cross section of typical H-gutter flame-holder unit, configurations A, B, and C.

Figure 4. - Commercial flame-holder and fuel-system units.



(b) Photograph and cross section of H-gutter flame-holder unit, configuration D.

Figure 4. - Continued. Commercial flame-holder and fuel-system units.

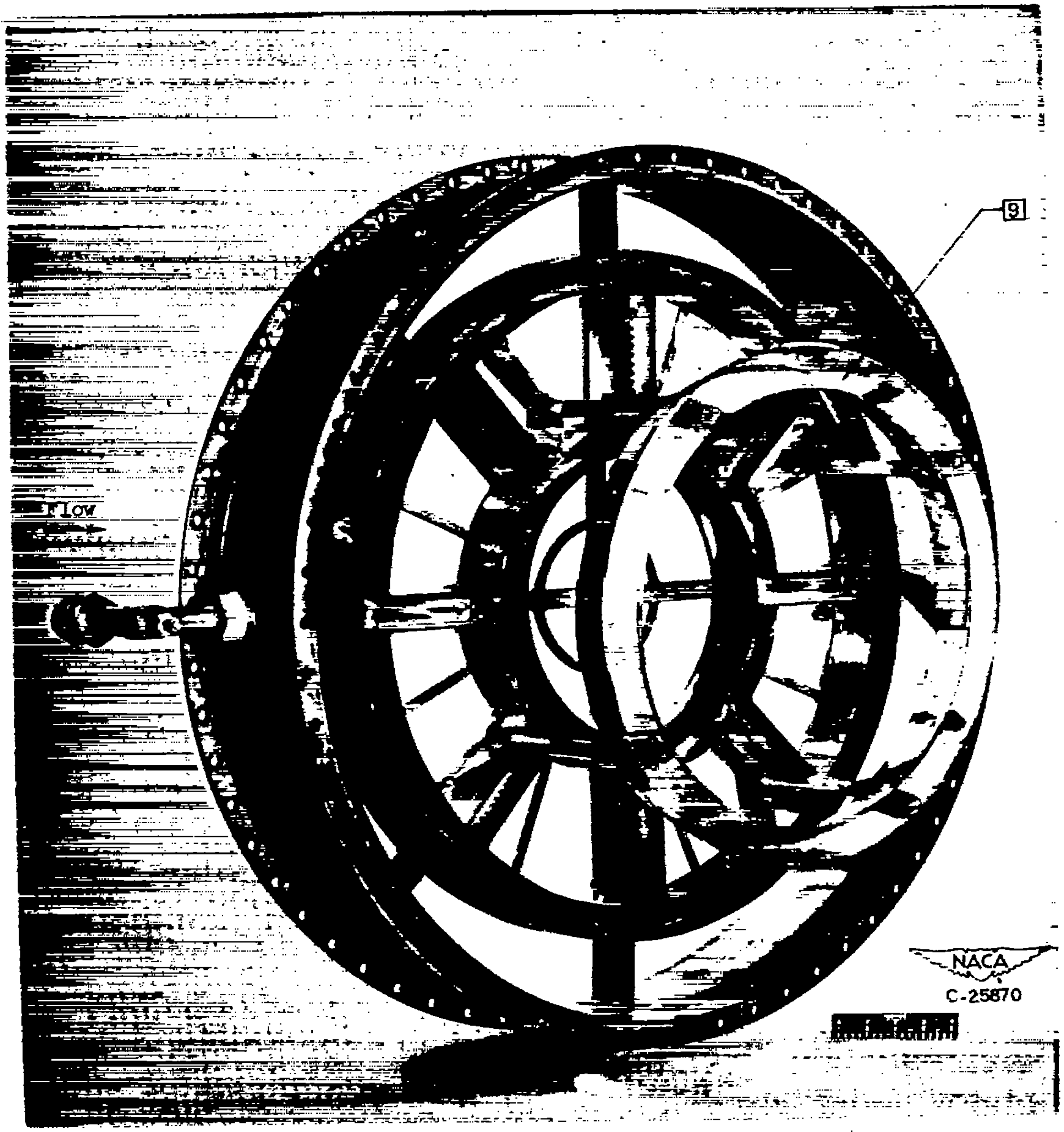


(c) Photograph and cross section of typical H-gutter flame-holder with trailing V-gutter, configurations E, F, and G.

Figure 4. - Continued. Commercial flame-holder and fuel-system units.

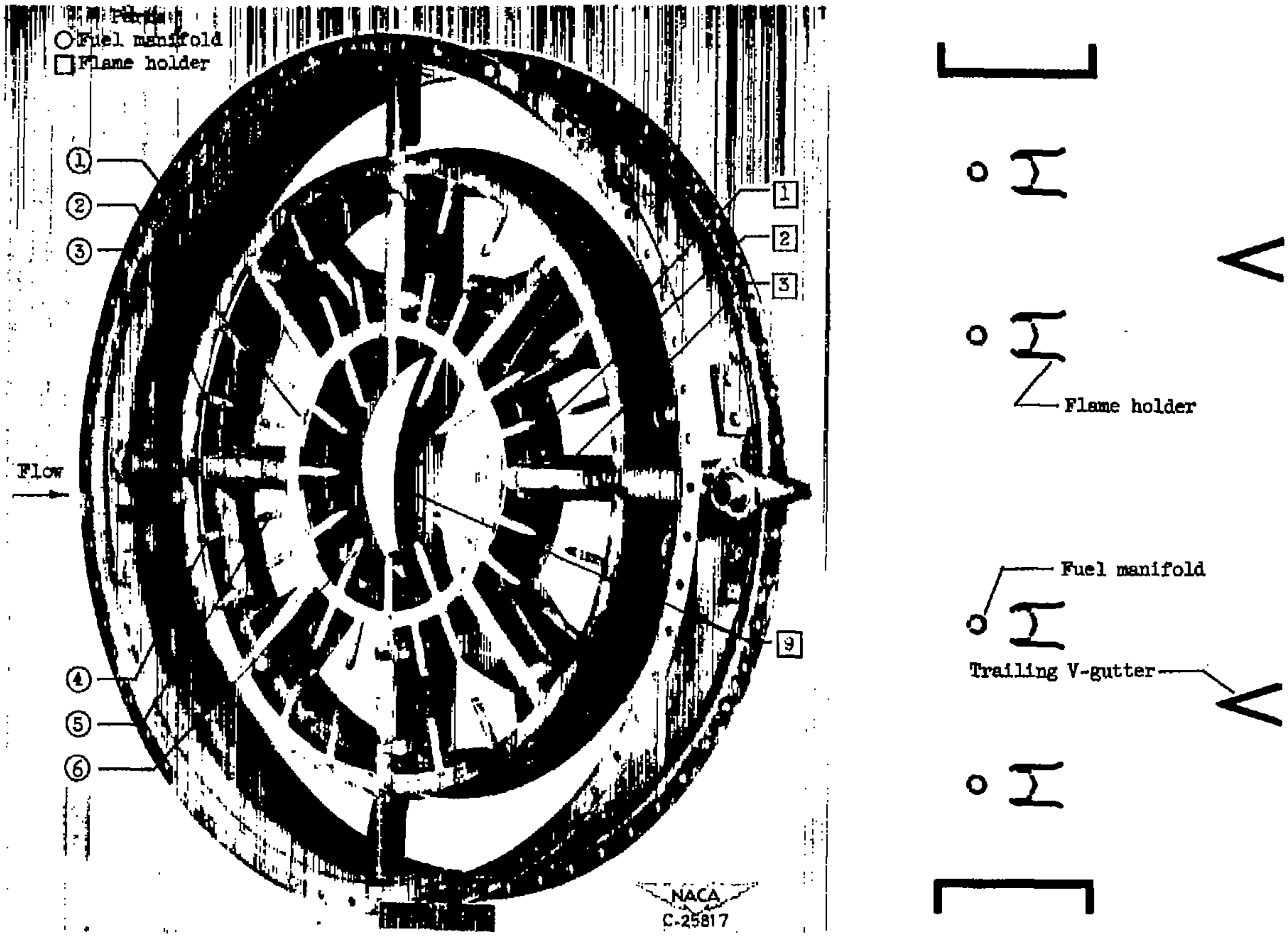
6T

2176

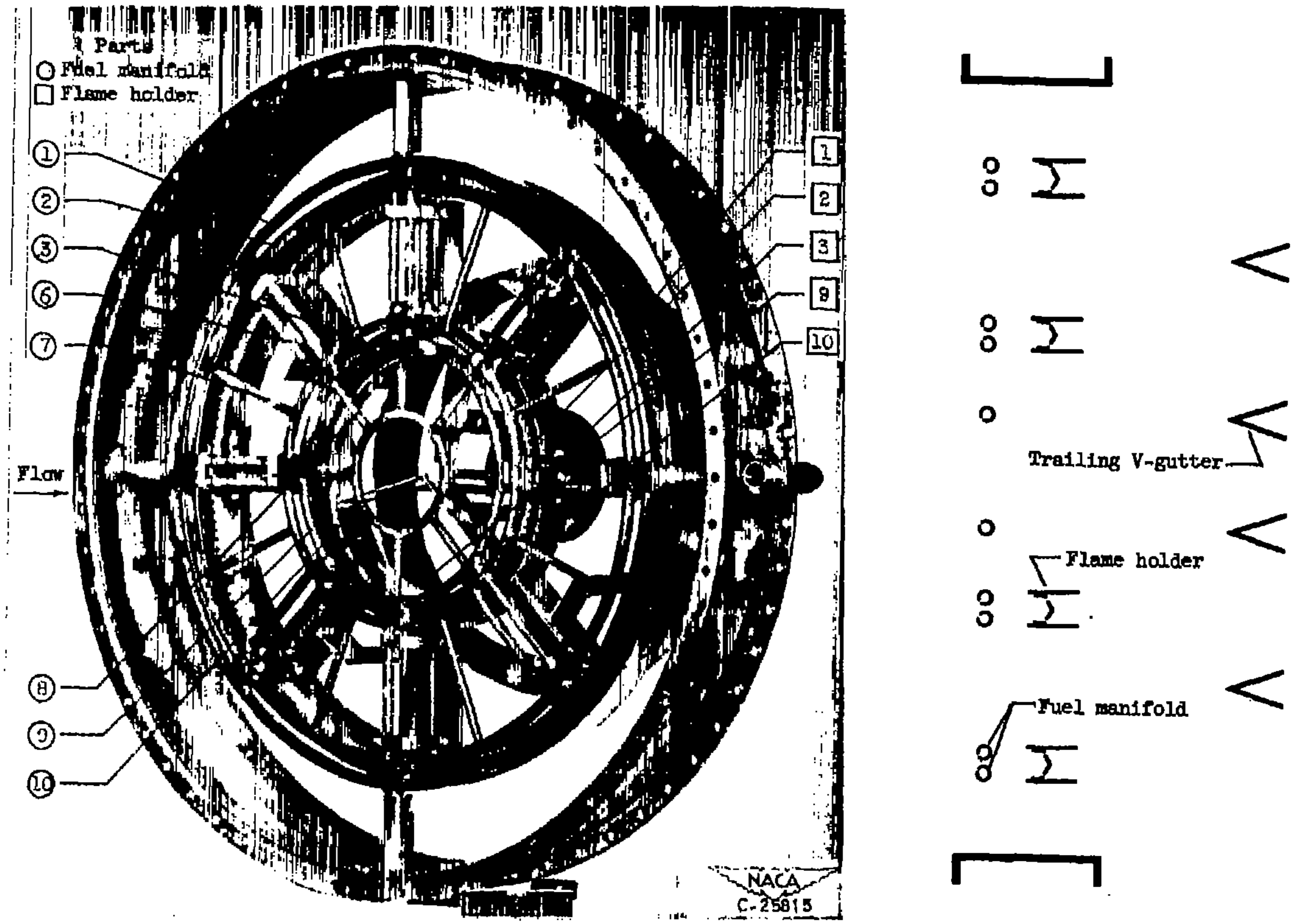


(d) Typical trailing V-gutter, configurations E, F, and G.

Figure 4. - Continued. Commercial flame-holder and fuel-system units.

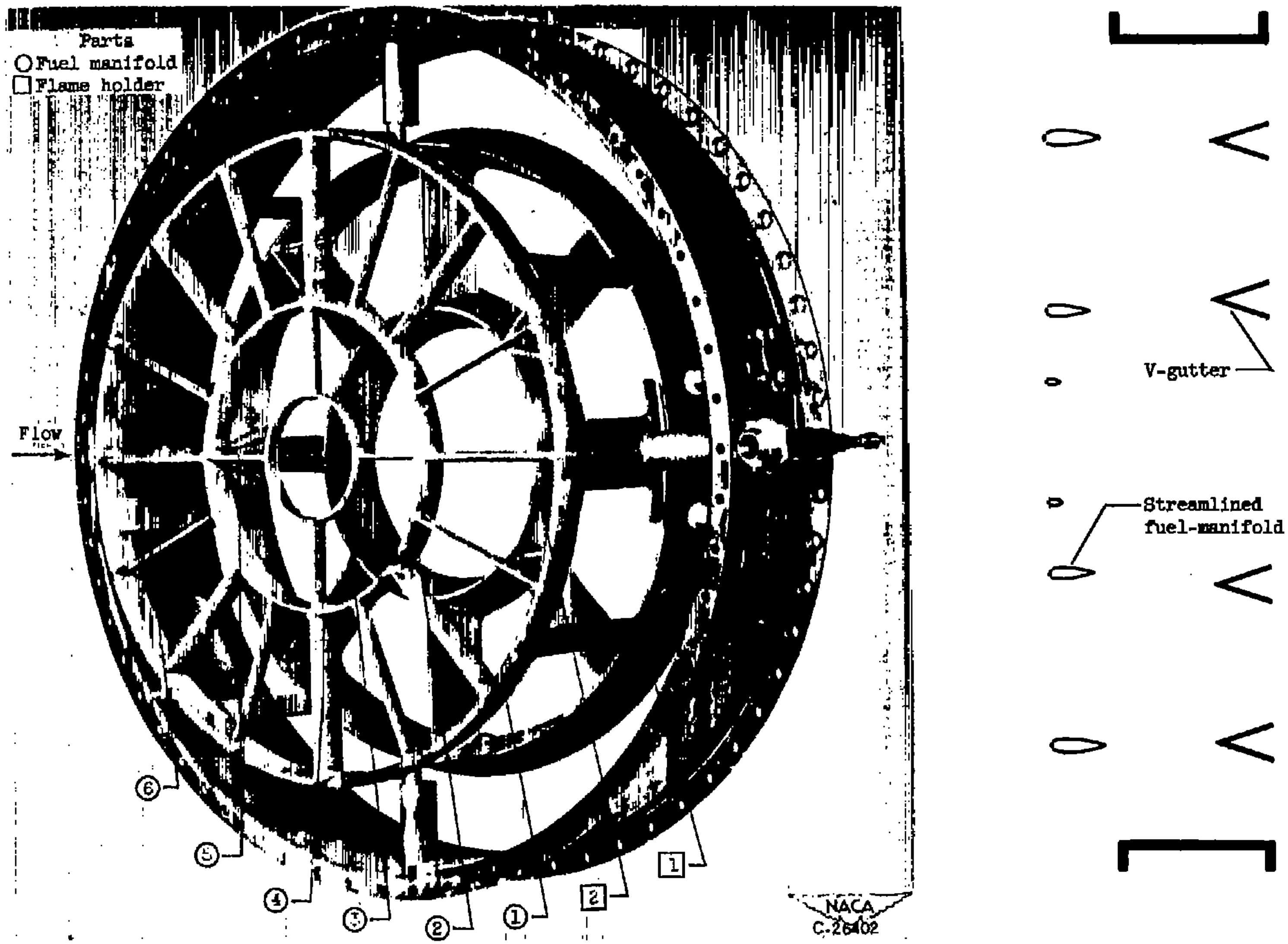


(e) Photograph and cross section of H-gutter with trailing V-gutter, configuration H.
Figure 4. - Continued. Commercial flame-holder and fuel-system units.



(f) Photograph and cross section of H-gutter flame holder with two trailing V-gutters, configuration I.

Figure 4. - Continued. Commercial flame-holder and fuel-system units.

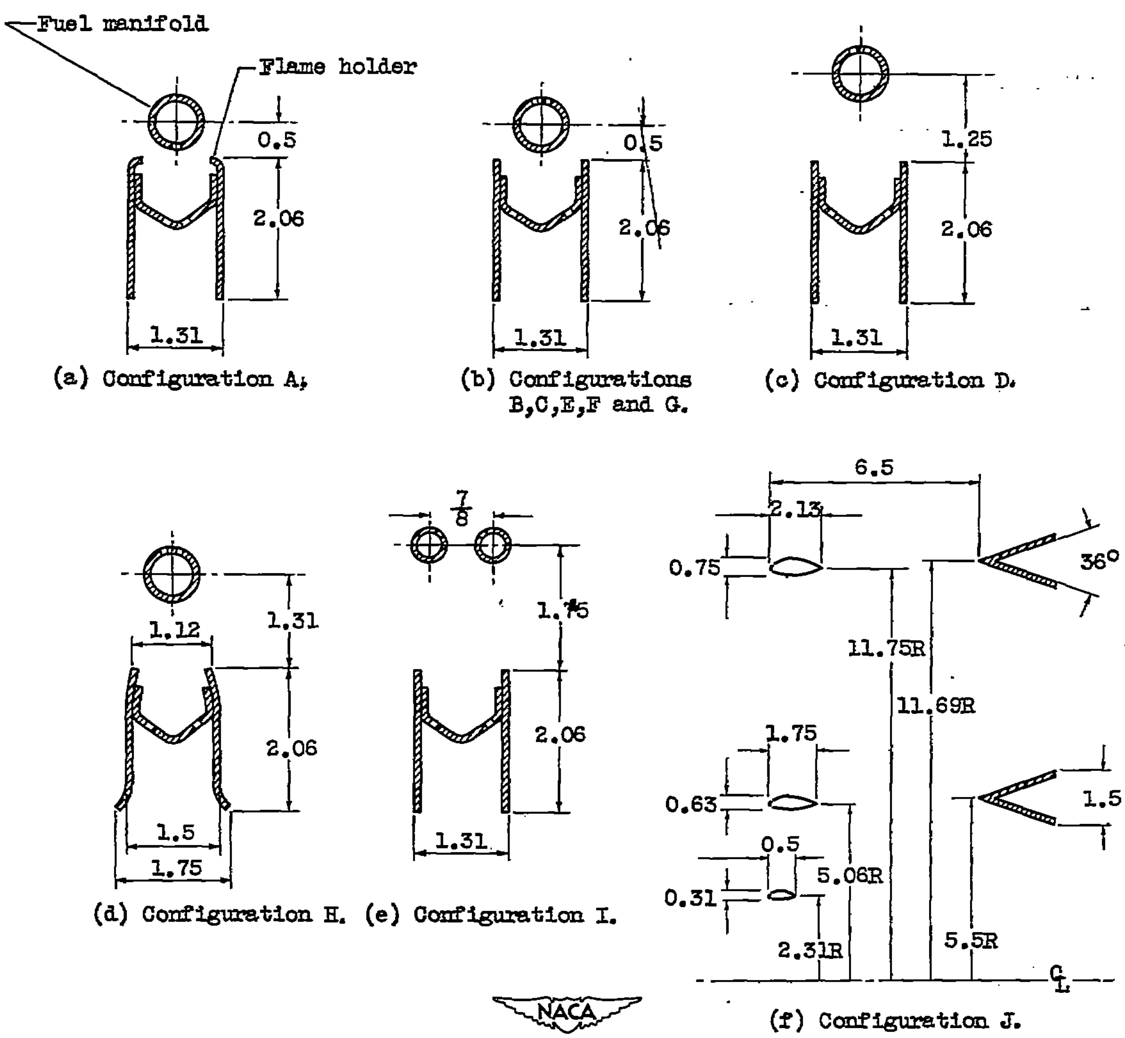


(g) Photograph and cross section of V-gutter flame holder, configuration J.

Figure 4. - Concluded. Commercial flame-holder and fuel-system units.

~~CONFIDENTIAL~~

2176



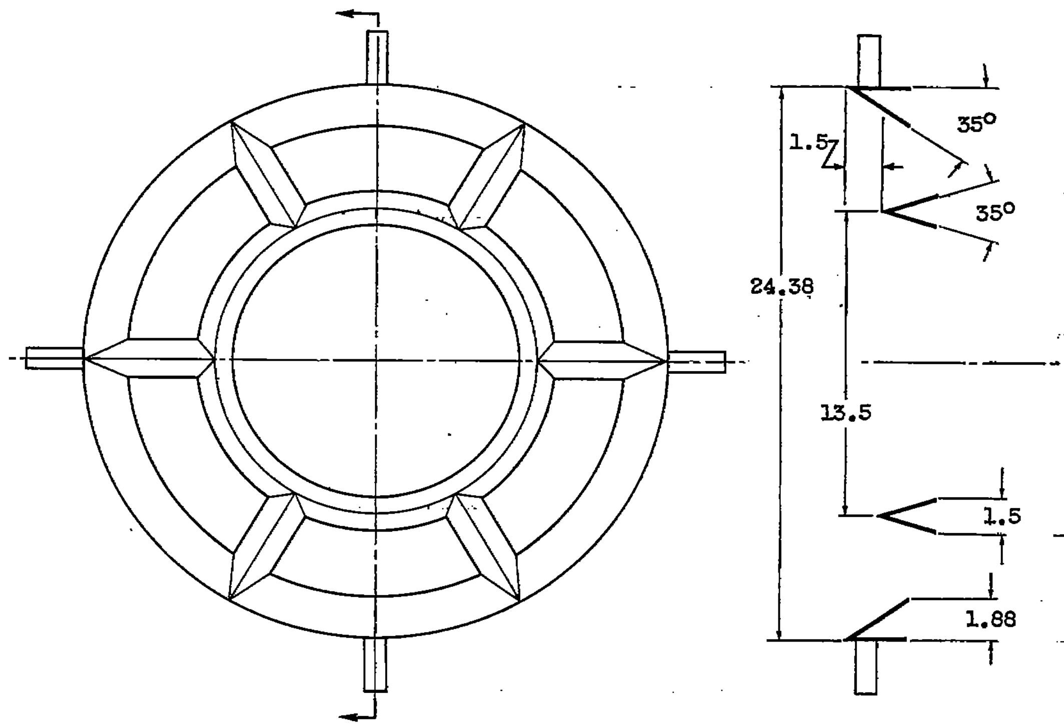
(a) Configuration A.
(b) Configurations B,C,E,F and G.
(c) Configuration D.
(d) Configuration H.
(e) Configuration I.
(f) Configuration J.

Figure 5. - Cross sections of commercial flame-holder and fuel-manifold units.

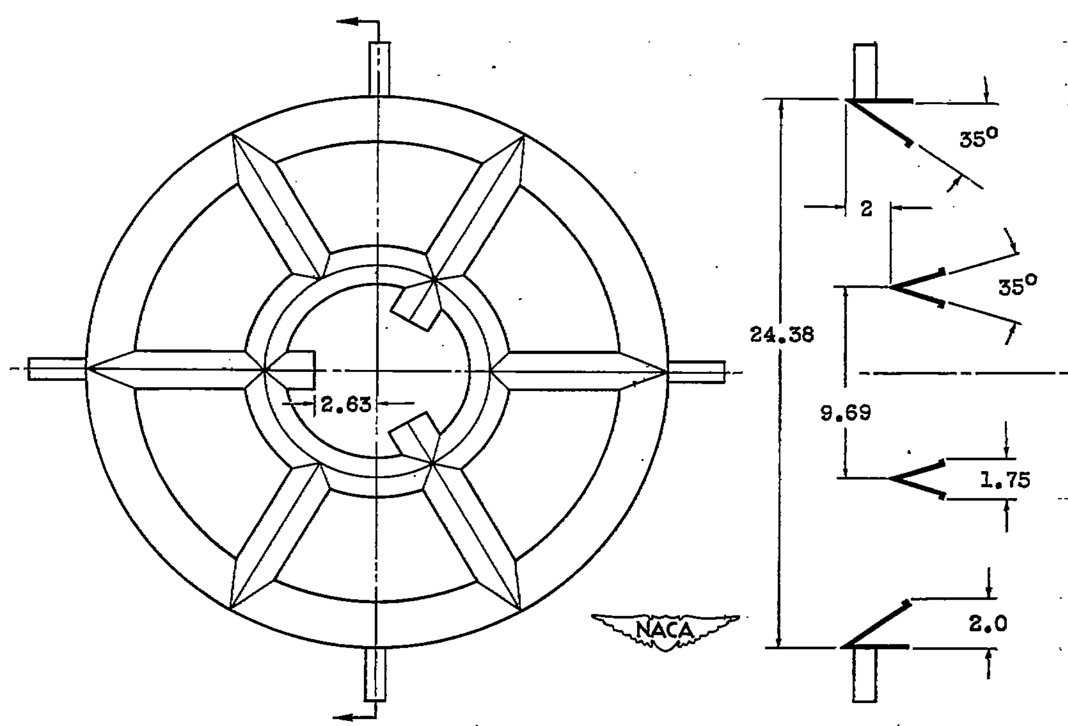
2150

[redacted]

2176



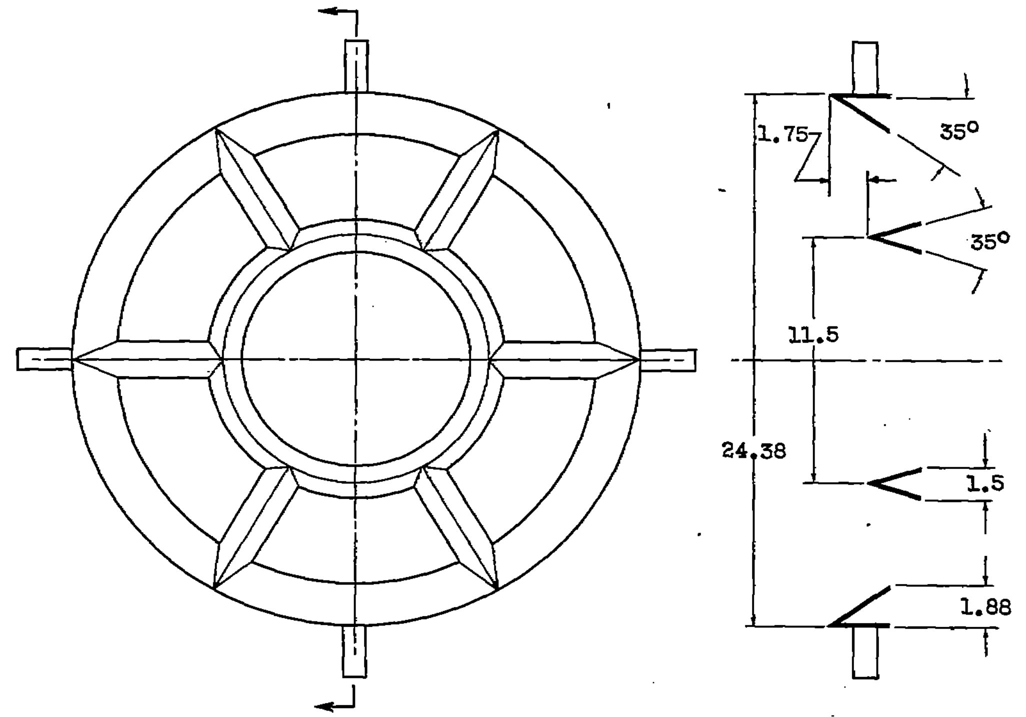
(a) Flame holder 1 used in configuration L and O.



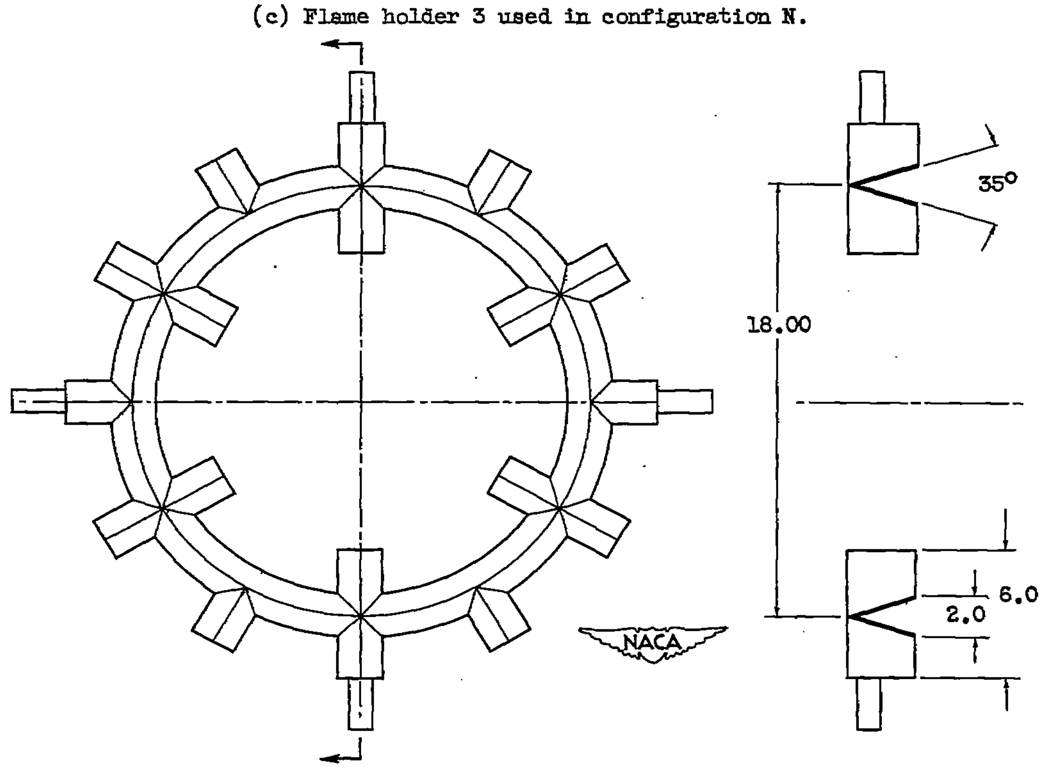
(b) Flame holder 2 used in configuration M.

Figure 6. - Schematic [redacted] designed flame holders.

2176



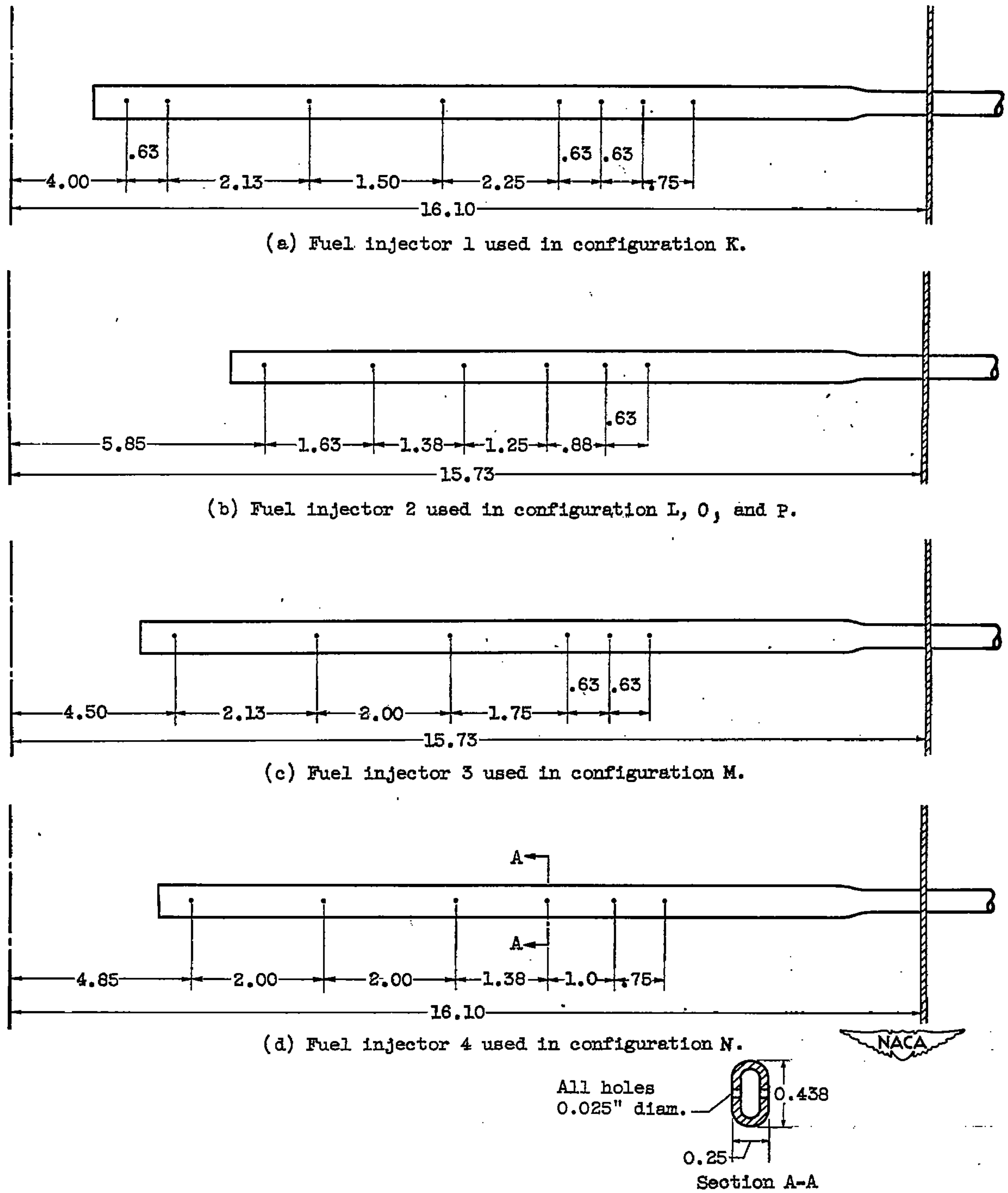
(c) Flame holder 3 used in configuration N.



(d) Flame holder 4 used in configuration P.

Figure 6. - Concluded. Schematic diagrams of NACA designed flame holders.

389-2155



(a) Fuel injector 1 used in configuration K.

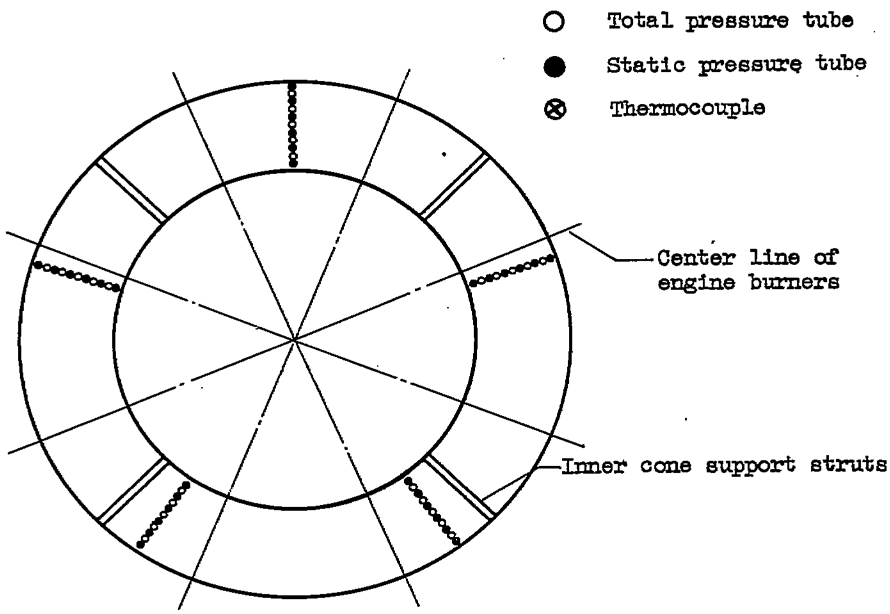
(b) Fuel injector 2 used in configuration L, O, and P.

(c) Fuel injector 3 used in configuration M.

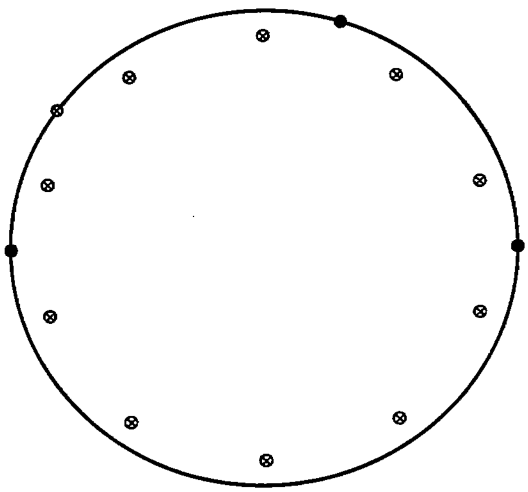
(d) Fuel injector 4 used in configuration N.

Figure 7. - Schematic diagrams of fuel injectors.

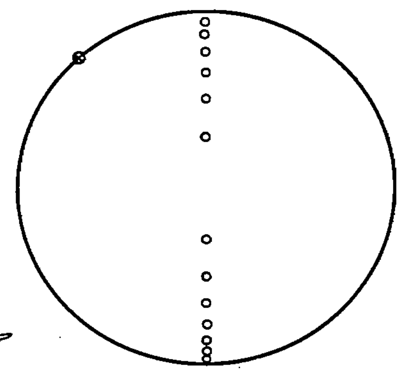
2176



(a) Turbine outlet (diffuser inlet), station 5, $4\frac{1}{2}$ inches downstream of turbine flange.



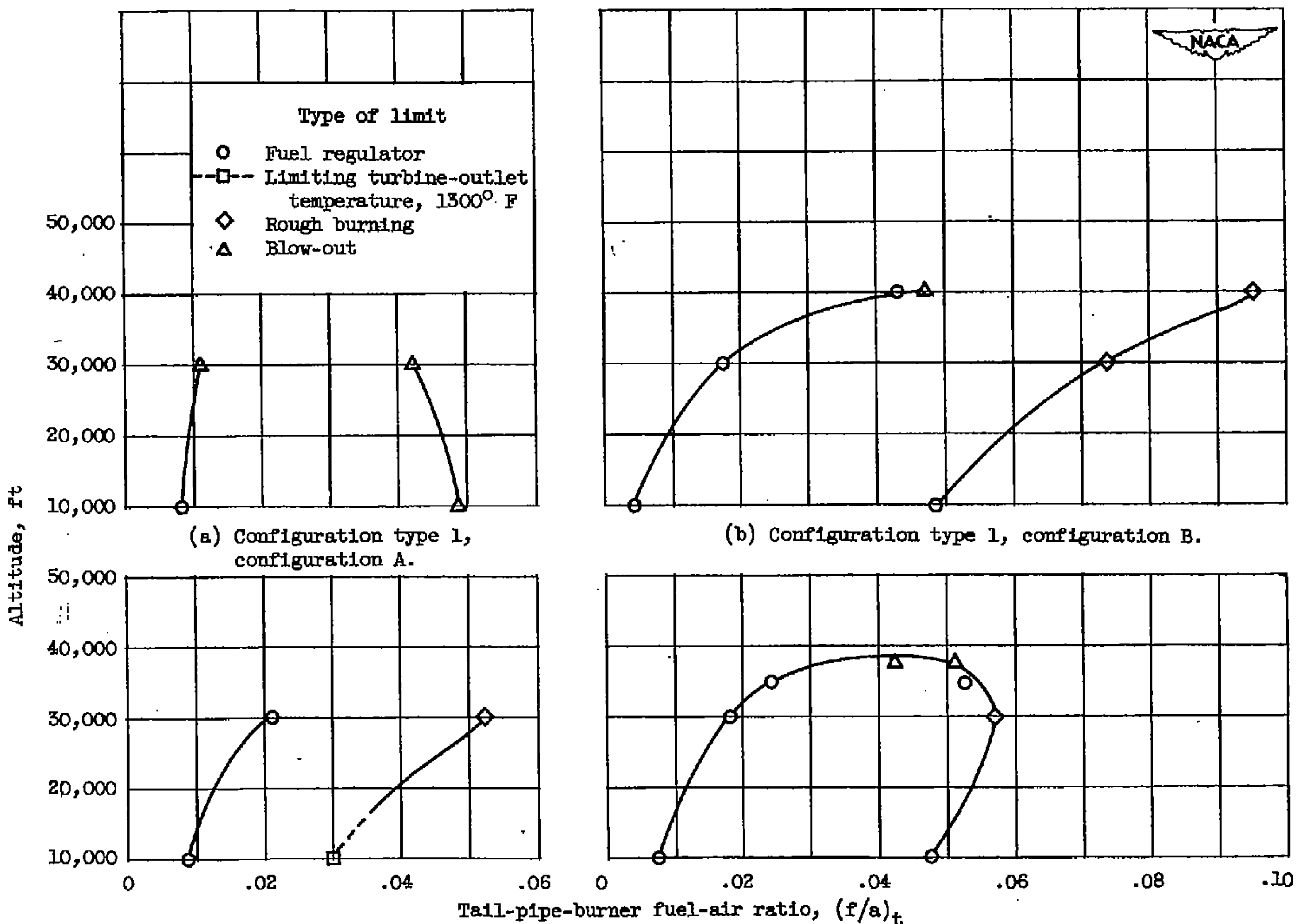
(b) Burner inlet, station 6, $1\frac{1}{2}$ inches upstream of diffuser outlet flange.



(c) Exhaust-nozzle inlet, station 7, 5 inches upstream of outlet.

Figure 8. - Location of pressure and temperature instrumentation installed in engine and tail-pipe burner; looking downstream.

389 - 2151



(a) Configuration type 1, configuration A.

(b) Configuration type 1, configuration B.

(c) Configuration type 1, configuration C.

(d) Configuration type 1, configuration D.

Figure 9. - Operable range of tail-pipe-burner configurations. Flight Mach number, 0.60.

[redacted]

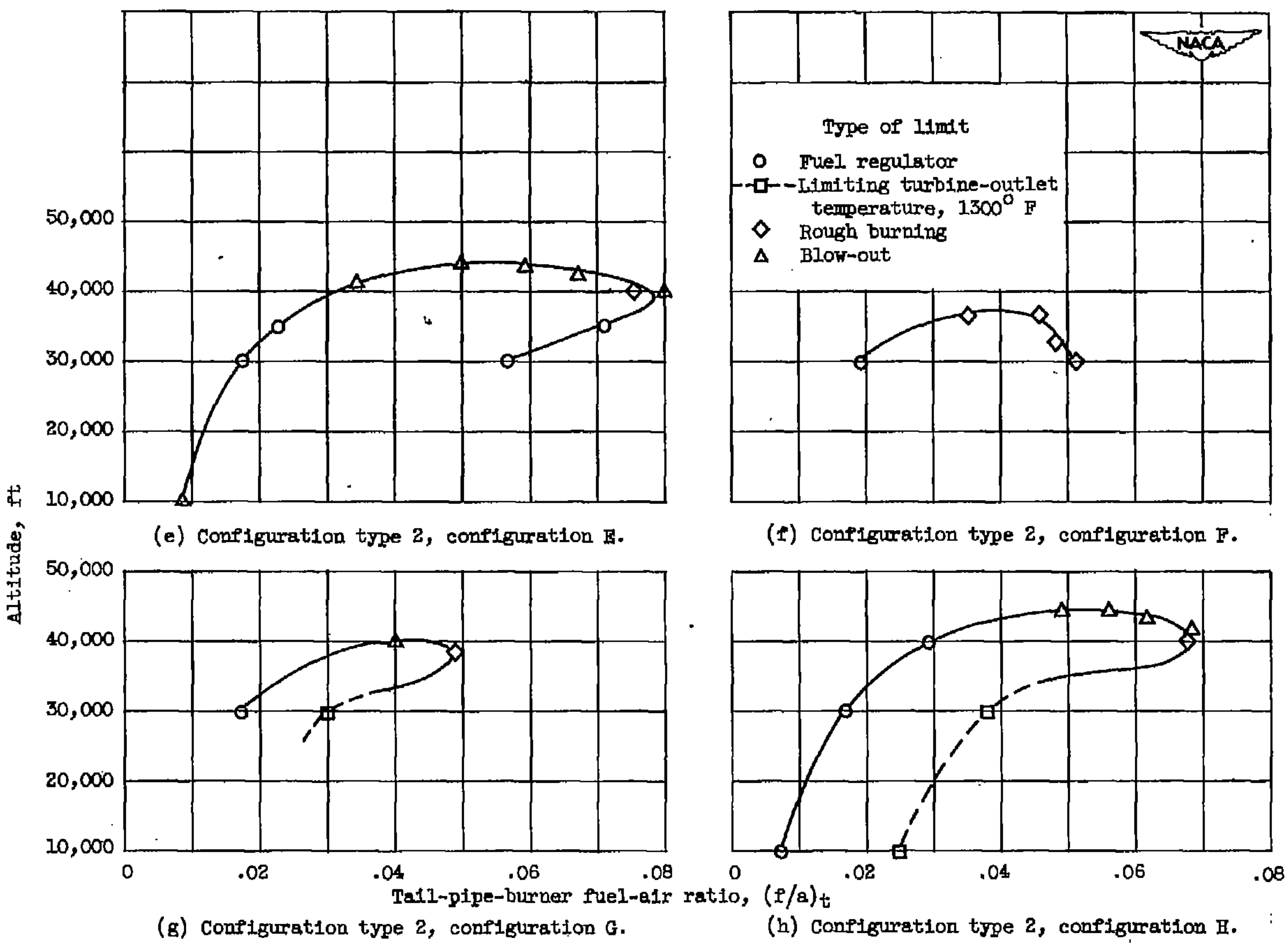
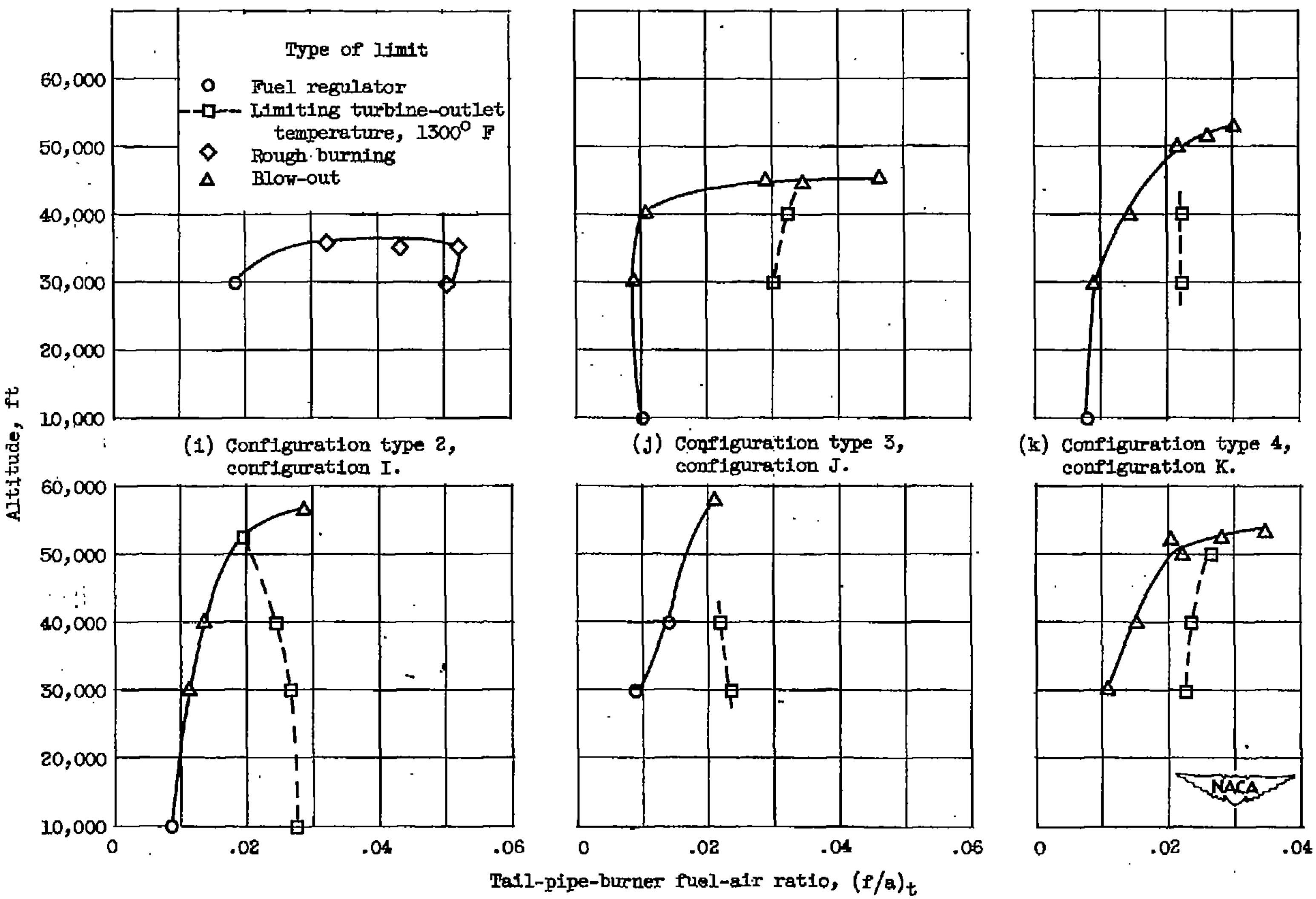


Figure 9. - Continued. Operable range of tail-pipe-burner configurations. Flight Mach number, 0.60.

[redacted]

CONFIDENTIAL



(i) Configuration type 2, configuration I.

(j) Configuration type 3, configuration J.

(k) Configuration type 4, configuration K.

(l) Configuration type 4, configuration L.

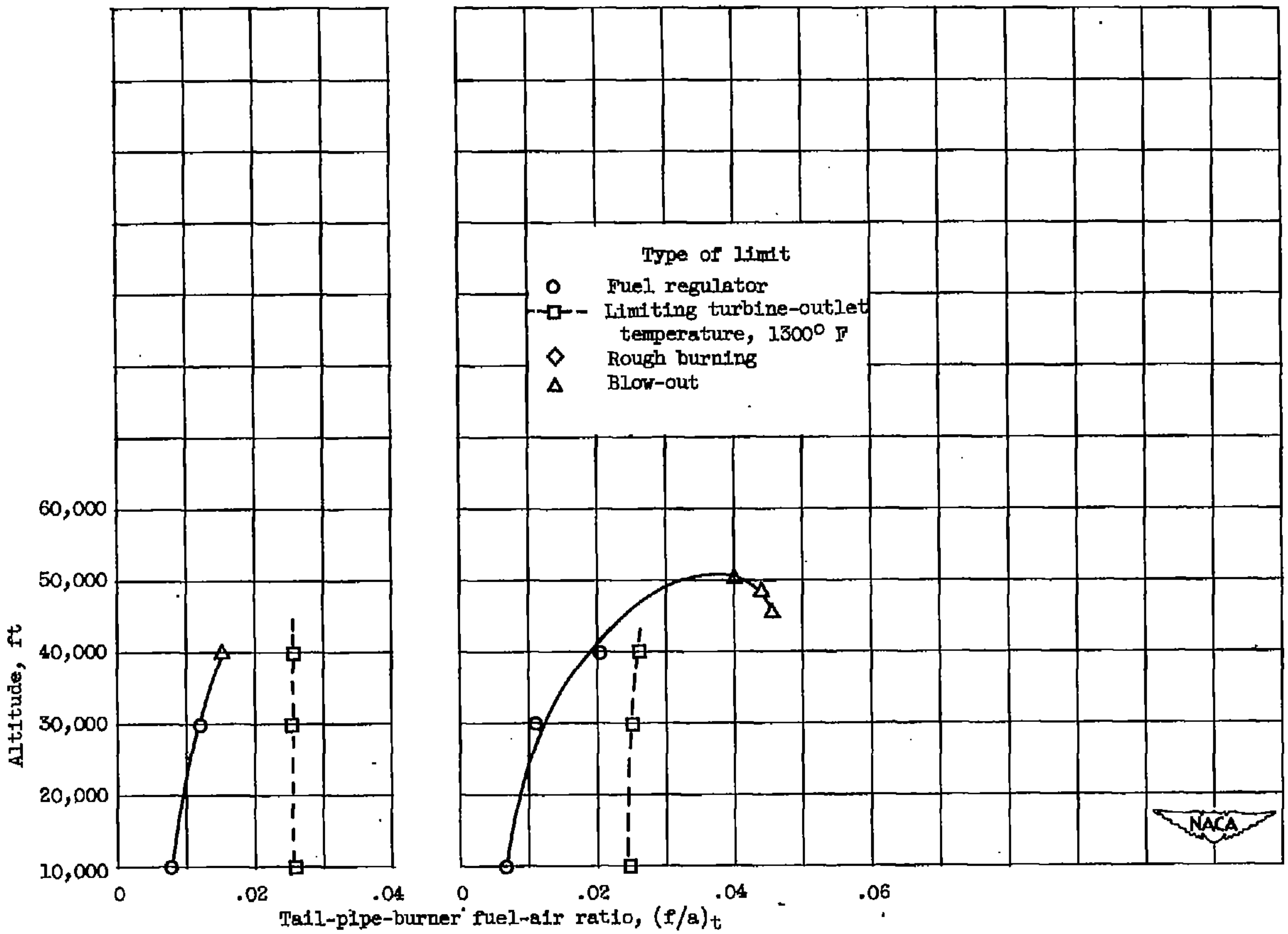
(m) Configuration type 4, configuration M.

(n) Configuration type 4, configuration N.

Figure 9. - Continued. Operable range of tail-pipe-burner configurations. Flight Mach number, 0.60.

[redacted]

[redacted]



(o) Configuration type 4, configuration O.

(p) Configuration type 5, configuration P.

Figure 9. - Concluded. Operable range of tail-pipe-burner configurations. Flight Mach number, 0.60.

[redacted]

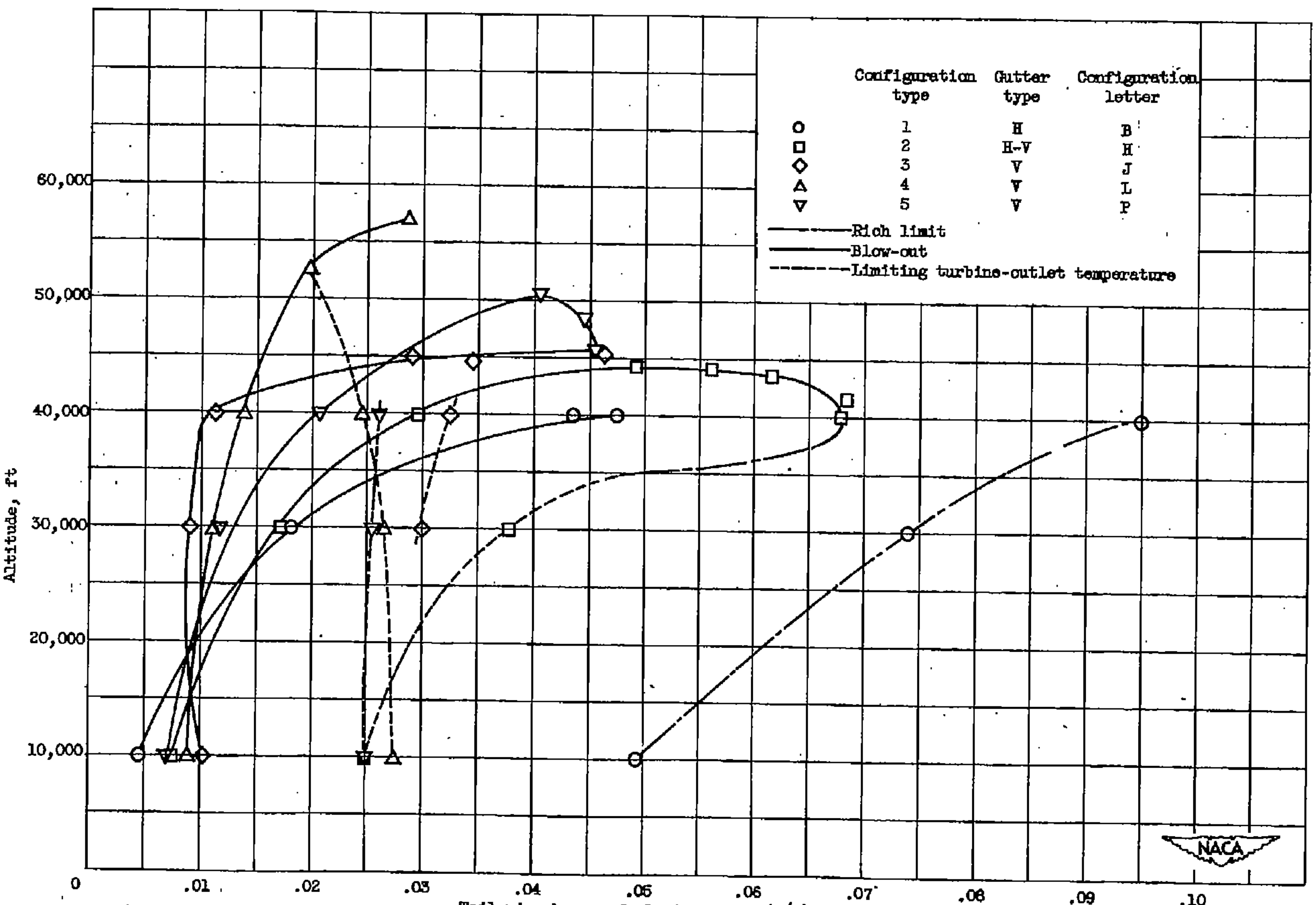
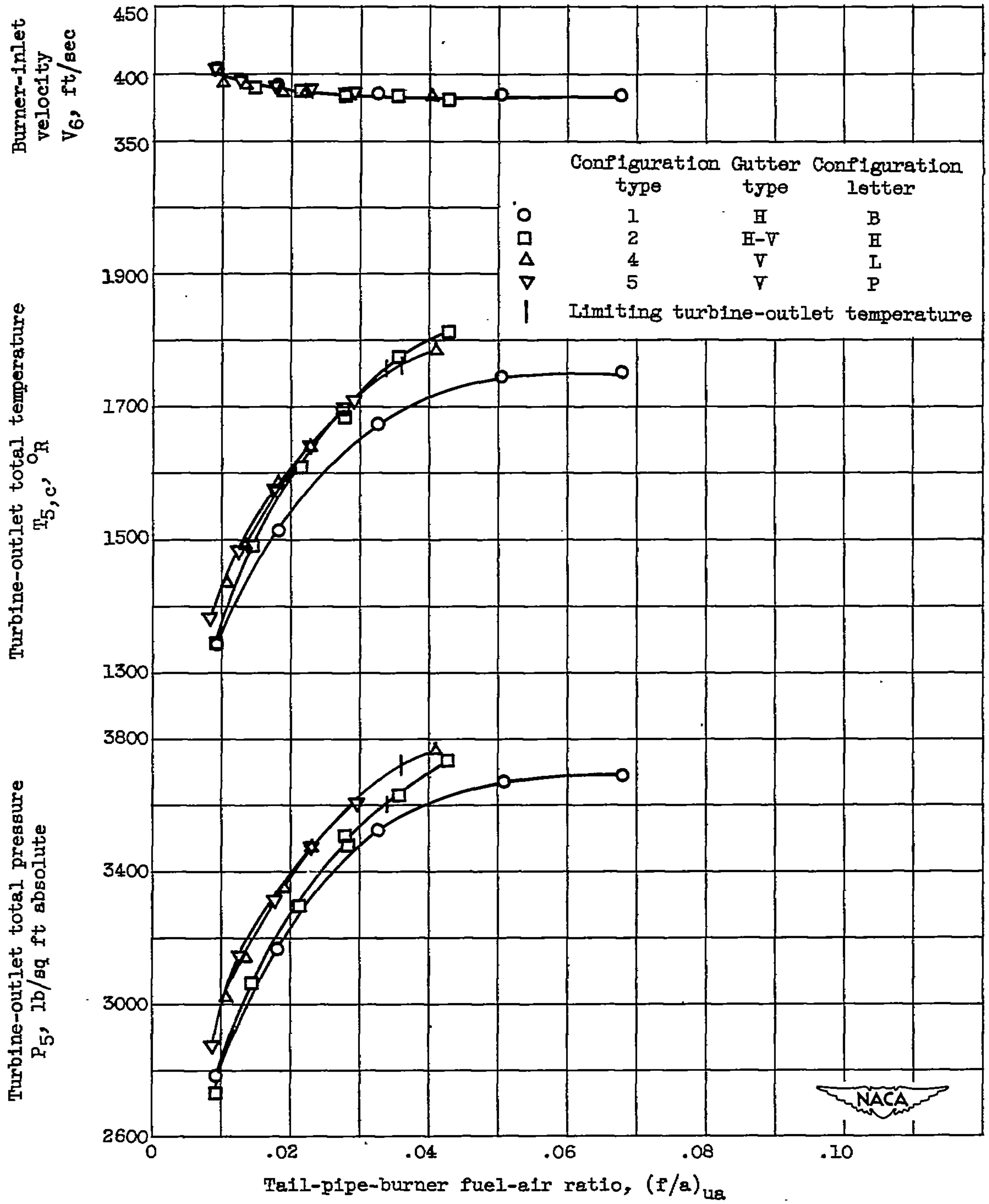


Figure 10. - Variation of operable range of several tail-pipe-burner configurations. Flight Mach number, 0.60.

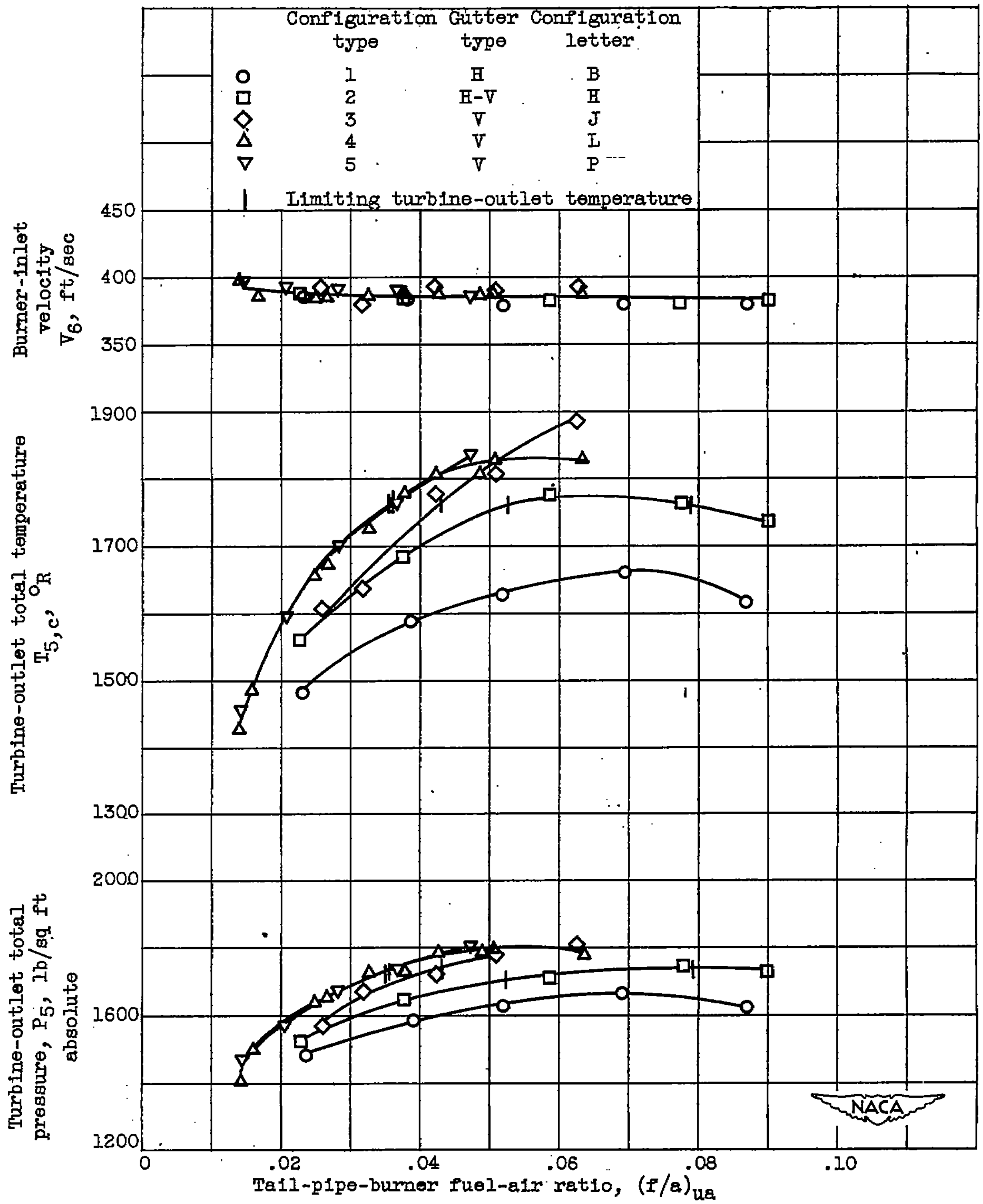
2176



(a) Altitude, 10,000 feet.

Figure 11. - Variations of tail-pipe-burner inlet conditions with tail-pipe-burner fuel-air ratio. Flight Mach number, 0.60.

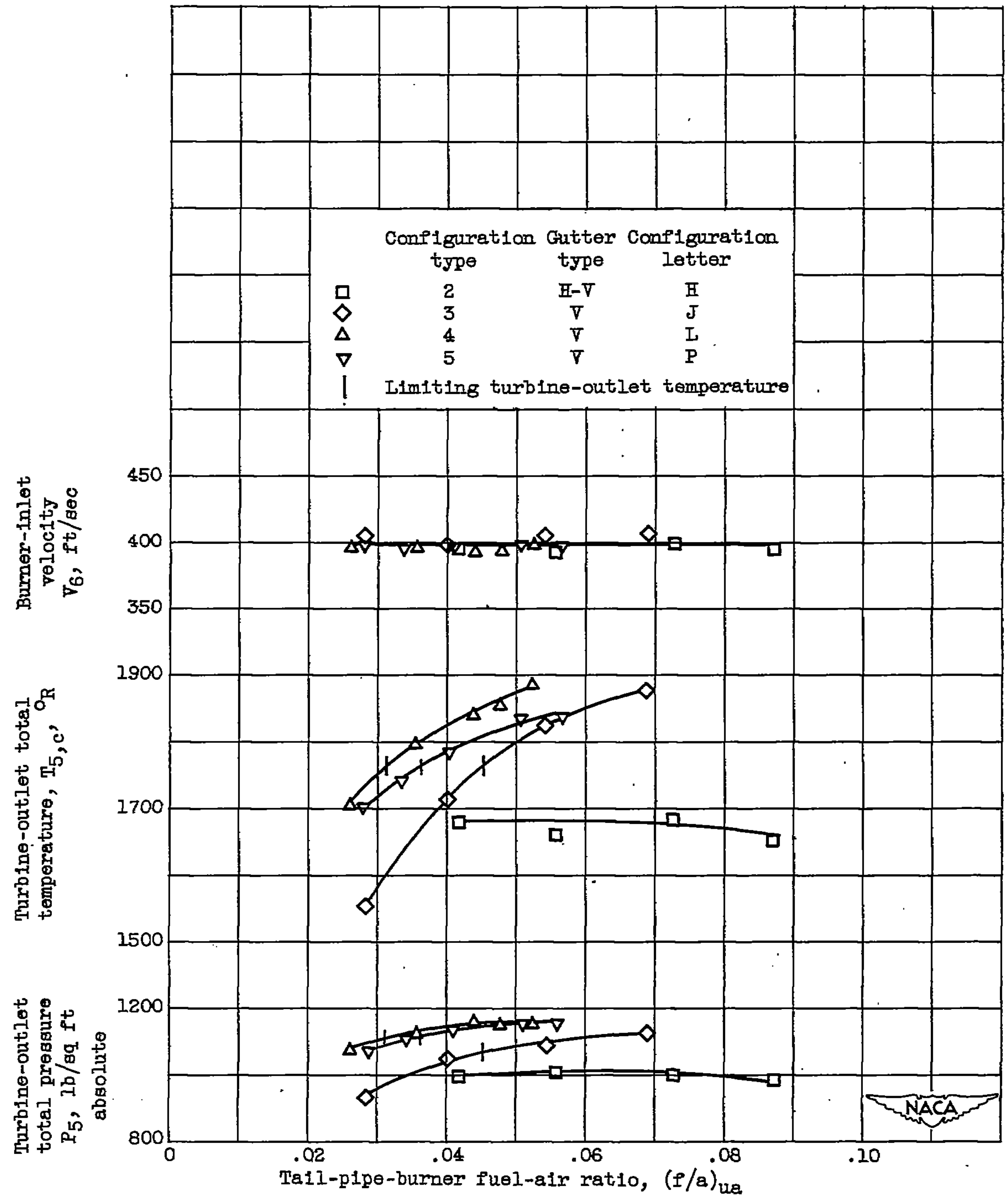
2176



(b) Altitude, 30,000 feet.

Figure 11. - Continued. Variations of tail-pipe-burner inlet conditions with tail-pipe-burner fuel-air ratio. Flight Mach number, 0.60.

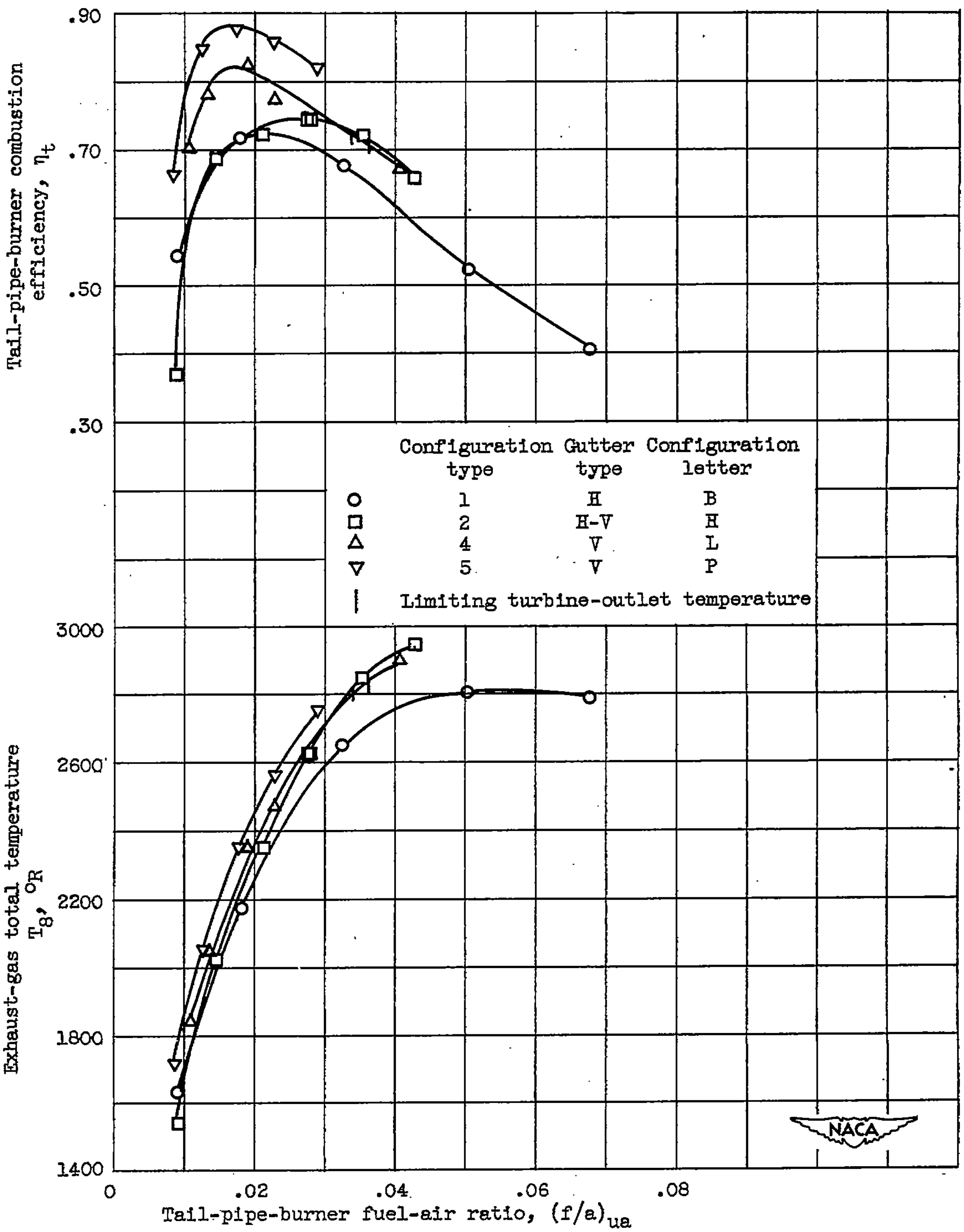
2176



(c) Altitude, 40,000 feet.

Figure 11. - Concluded. Variations of tail-pipe-burner inlet conditions with tail-pipe-burner fuel-air ratio. Flight Mach number, 0.60.

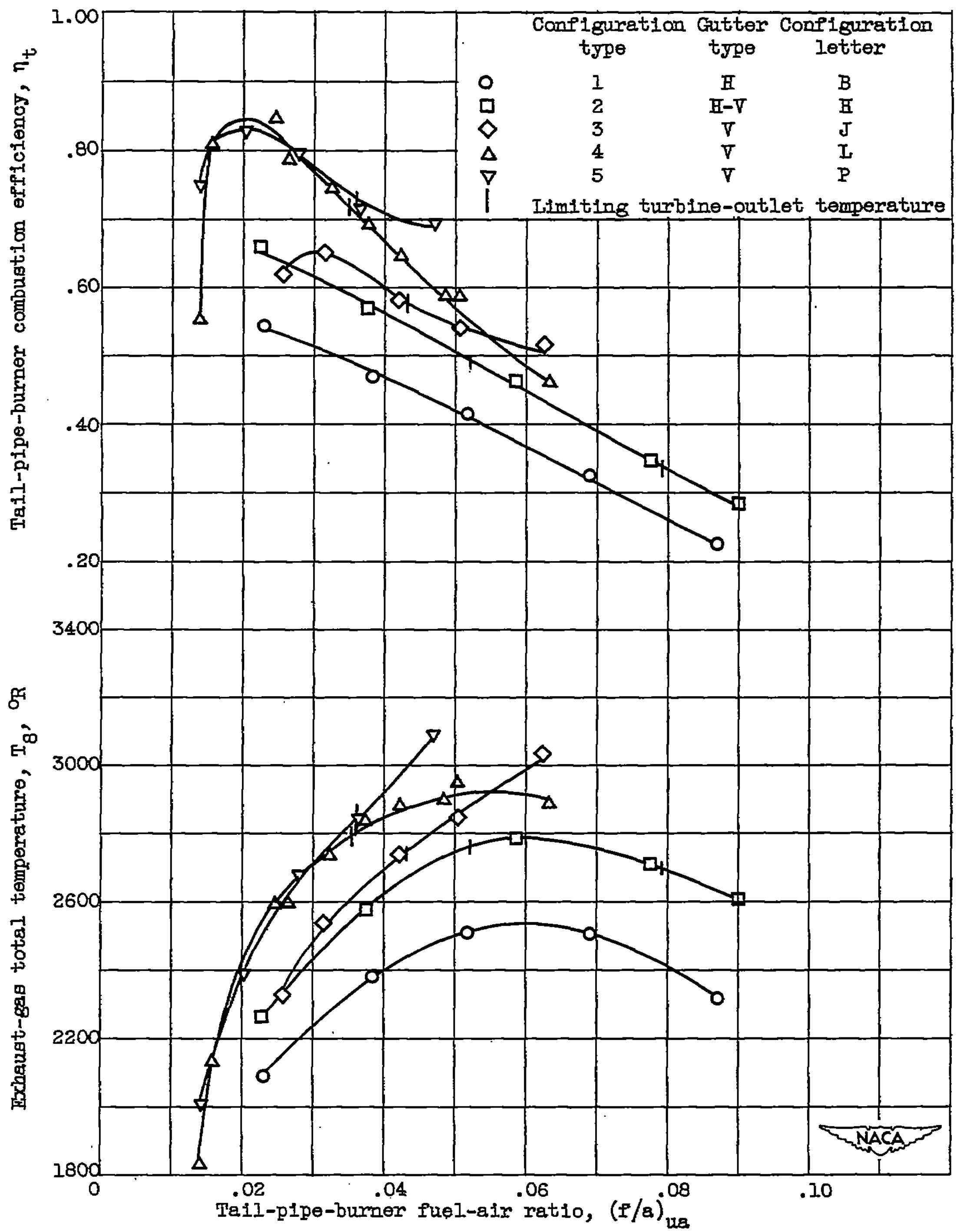
2176



(a) Altitude, 10,000 feet.

Figure 12. - Variations of tail-pipe-burner combustion efficiency and exhaust-gas total temperature with tail-pipe-burner fuel-air ratio. Flight Mach number, 0.60.

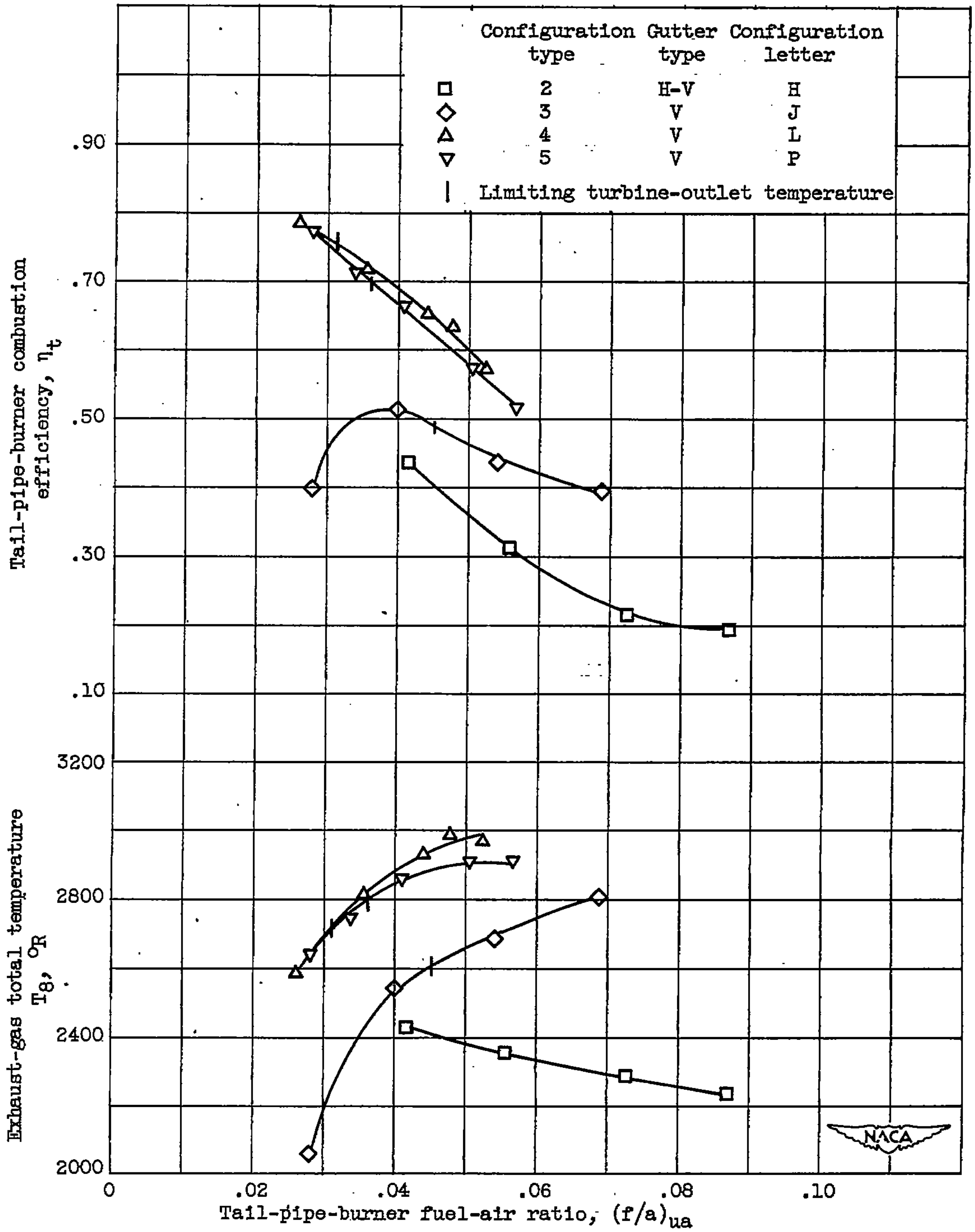
2176



(b) Altitude, 30,000 feet.

Figure 12. - Continued. Variations of tail-pipe-burner combustion efficiency and exhaust-gas total temperature with tail-pipe-burner fuel-air ratio. Flight Mach number, 0.60.

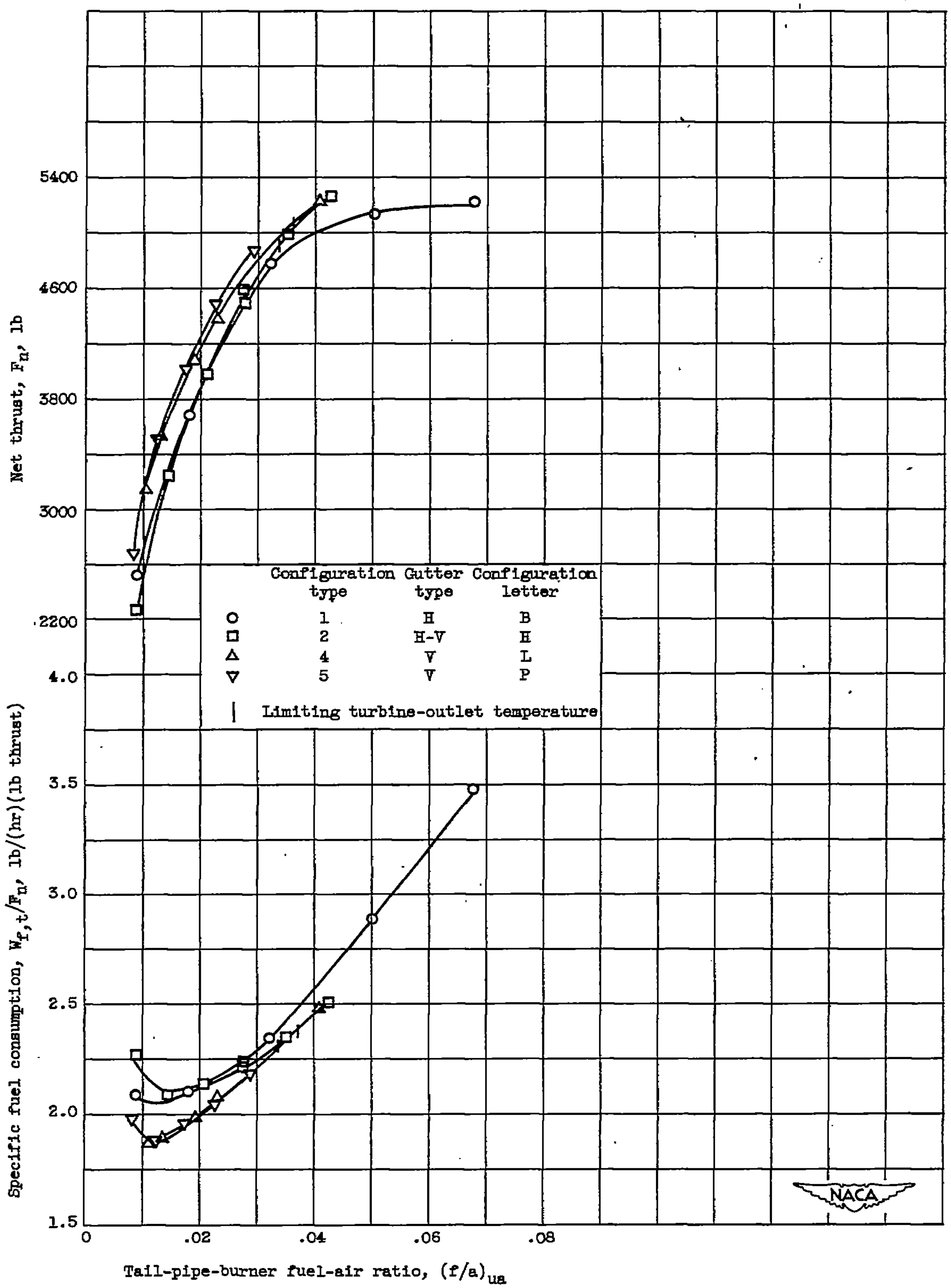
2176



(c) Altitude, 40,000 feet.

Figure 12. - Concluded. Variations of tail-pipe-burner combustion efficiency and exhaust-gas total temperature with tail-pipe-burner fuel-air ratio. Flight Mach number, 0.60.

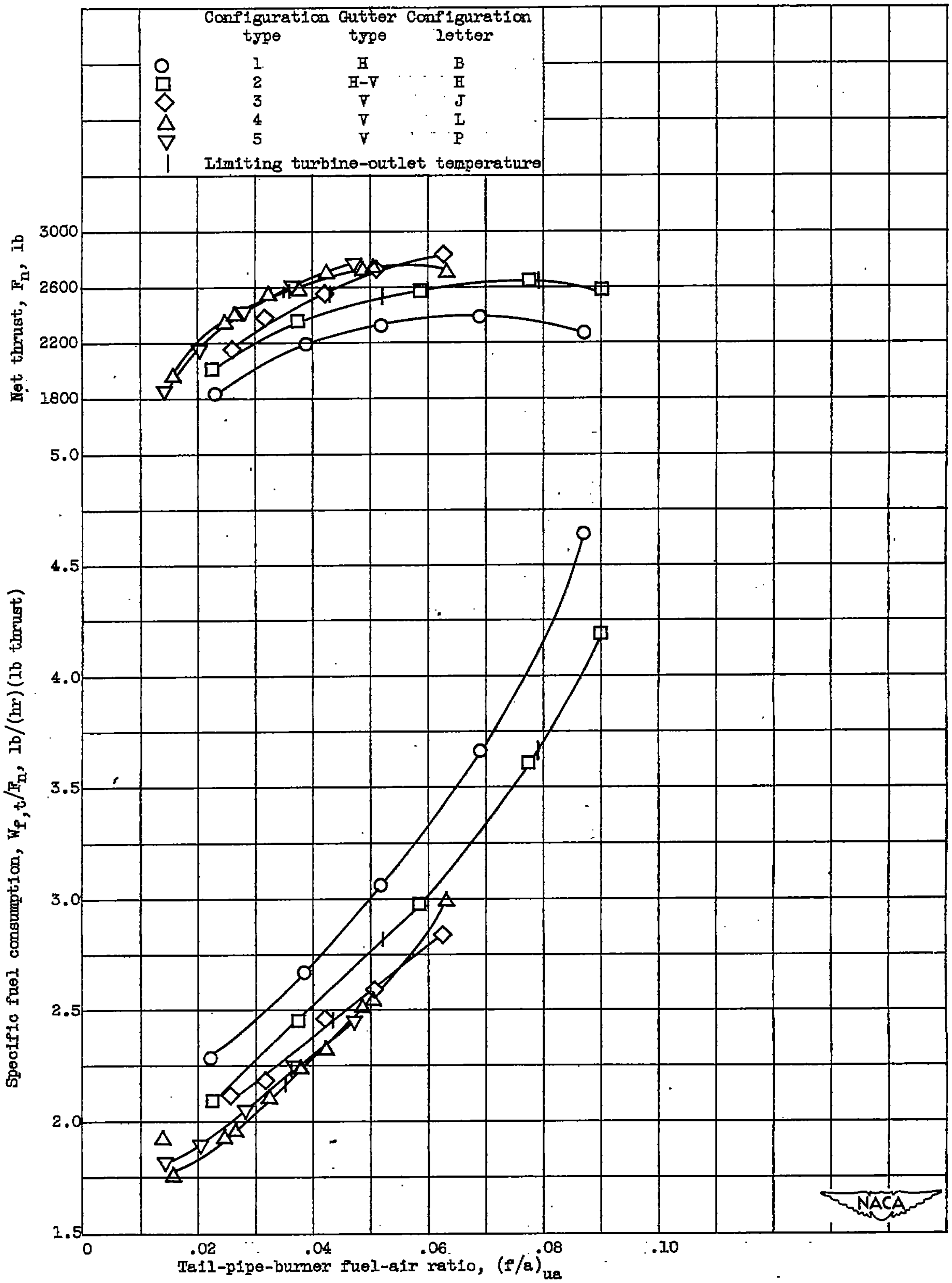
2176



(a) Altitude, 10,000 feet.

Figure 13. - Variations of specific fuel consumption and net thrust with tail-pipe-burner fuel-air ratio. Flight Mach number, 0.60.

[redacted]

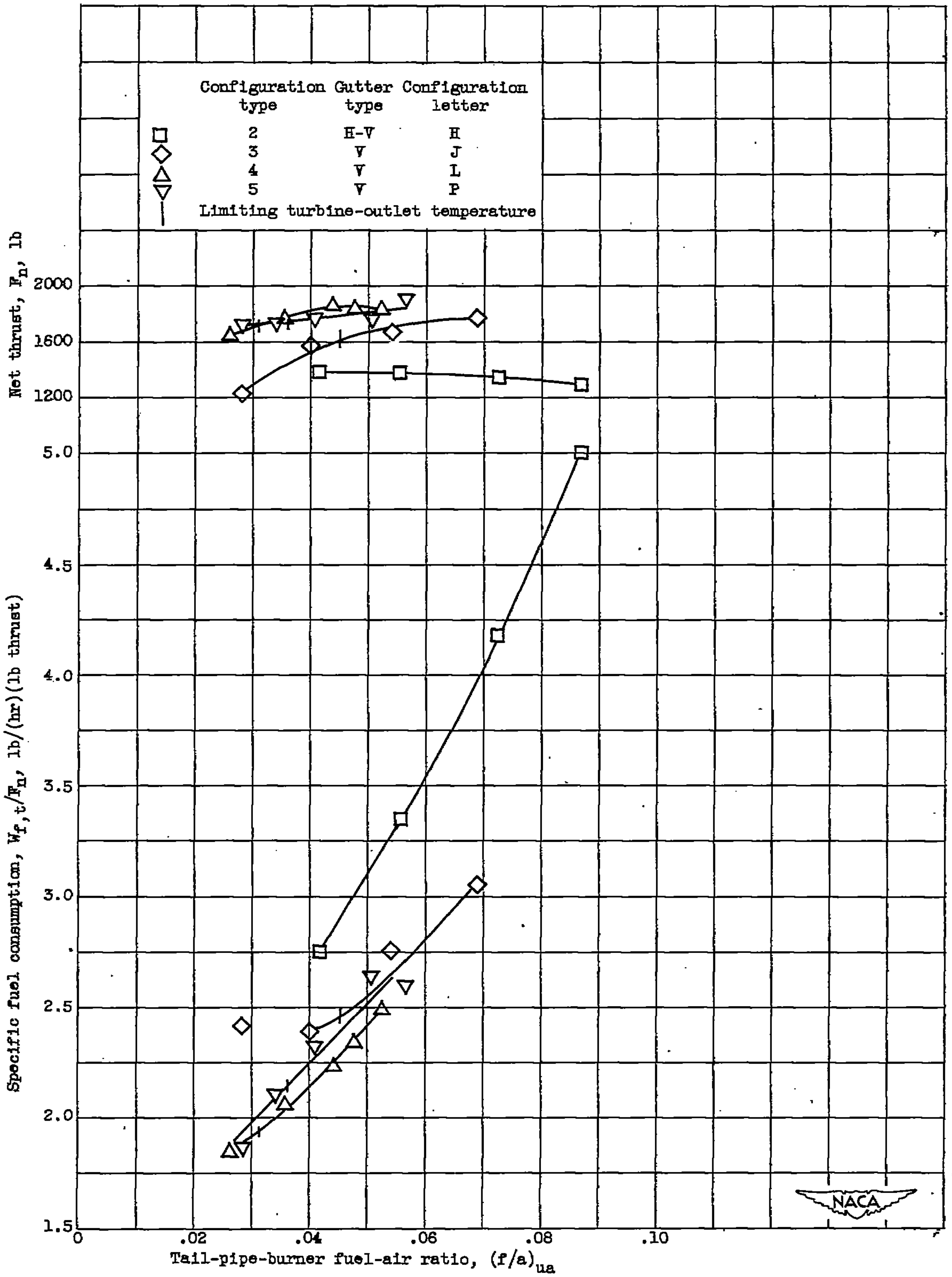


(b) Altitude, 30,000 feet.

Figure 13. - Continued. Variations of specific fuel consumption and net thrust with tail-pipe-burner fuel-air ratio. Flight Mach number, 0.60.

2176

2176



(c) Altitude, 40,000 feet.

Figure 13. - Concluded. Variations of specific fuel consumption and net thrust with tail-pipe-burner fuel-air ratio. Flight Mach number, 0.60.

[redacted]

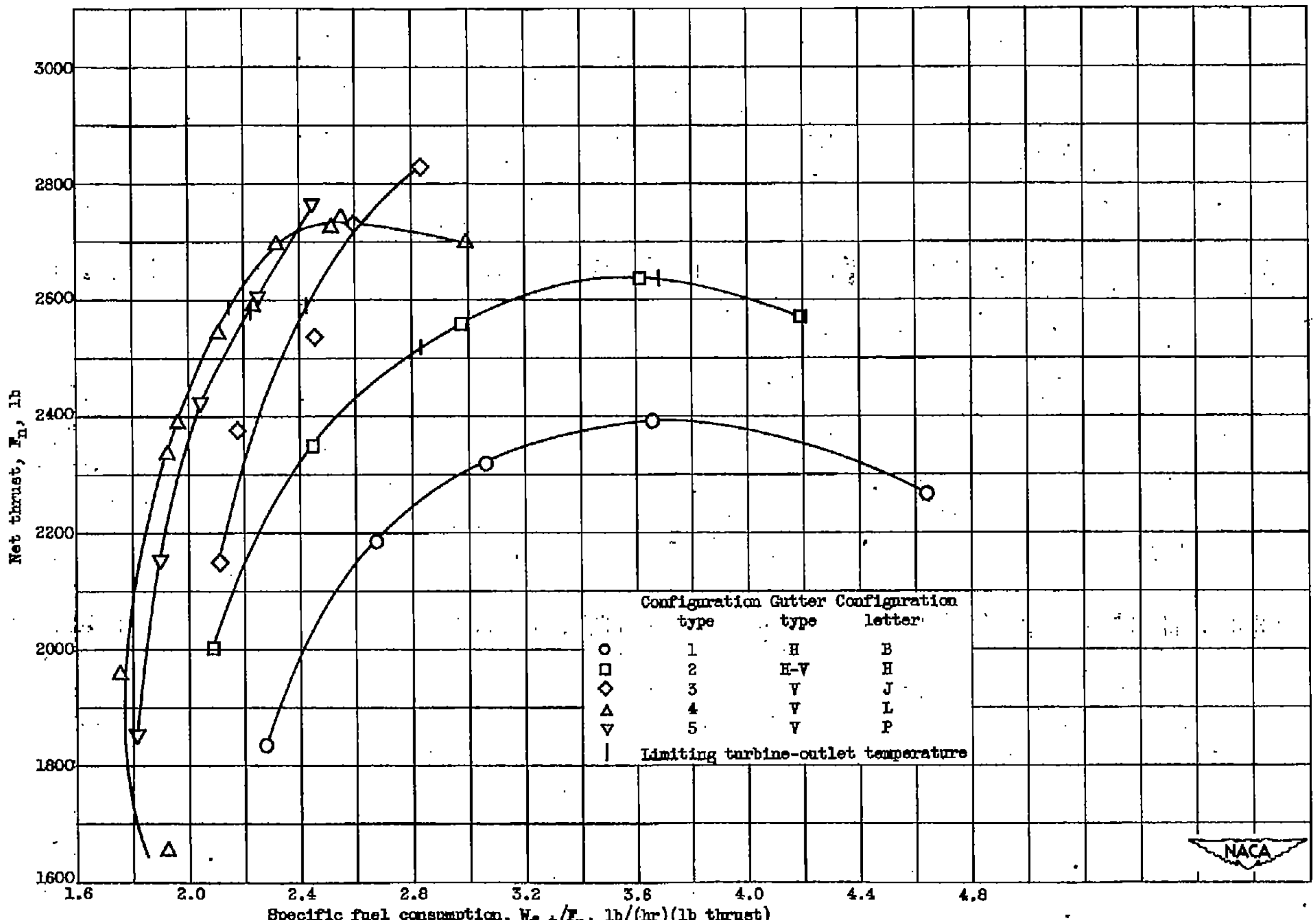
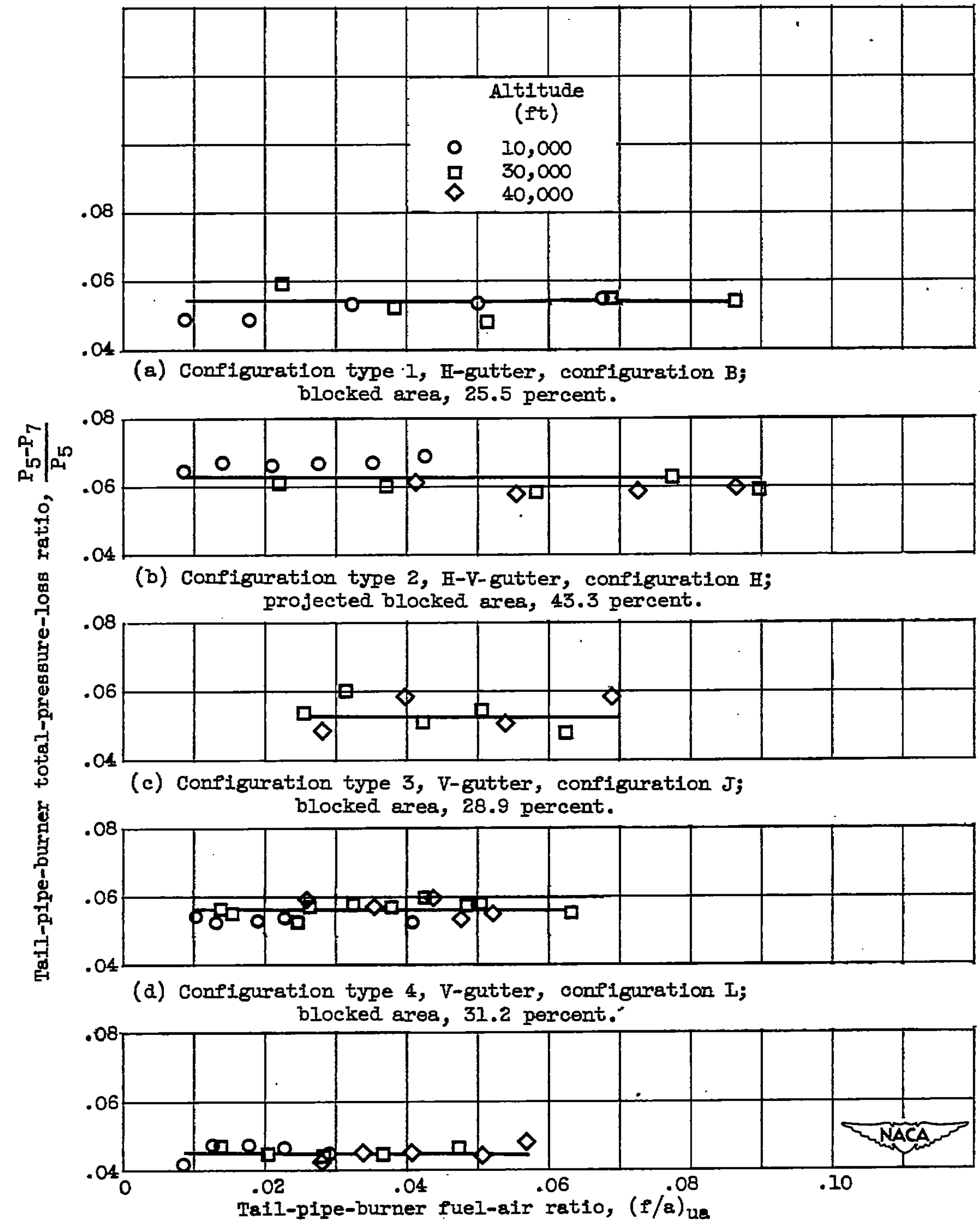


Figure 14. - Variation of net thrust and specific fuel consumption for several configurations at altitude of 30,000 feet and flight Mach number of 0.60.

2176



(a) Configuration type 1, H-gutter, configuration B; blocked area, 25.5 percent.

(b) Configuration type 2, H-V-gutter, configuration H; projected blocked area, 43.3 percent.

(c) Configuration type 3, V-gutter, configuration J; blocked area, 28.9 percent.

(d) Configuration type 4, V-gutter, configuration L; blocked area, 31.2 percent.

(e) Configuration type 5, V-gutter, configuration P; blocked area, 26.6 percent.

Figure 15. - Variation of tail-pipe-burner total-pressure-loss ratio with tail-pipe-burner fuel-air ratio. Flight Mach number, 0.60.

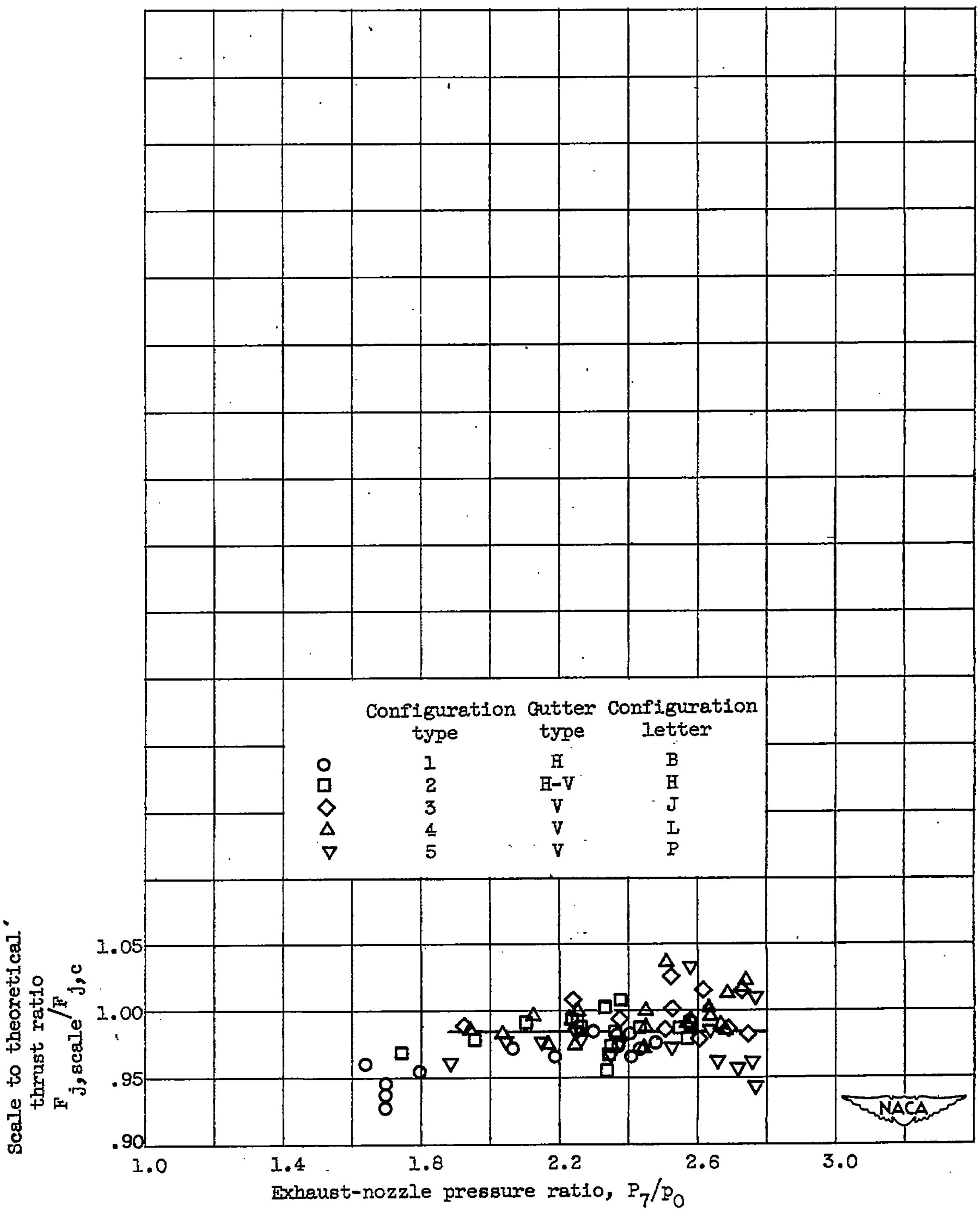


Figure 16. - Variations of tail-pipe-burner scale to theoretical thrust ratio with exhaust-nozzle pressure ratio.

[redacted]

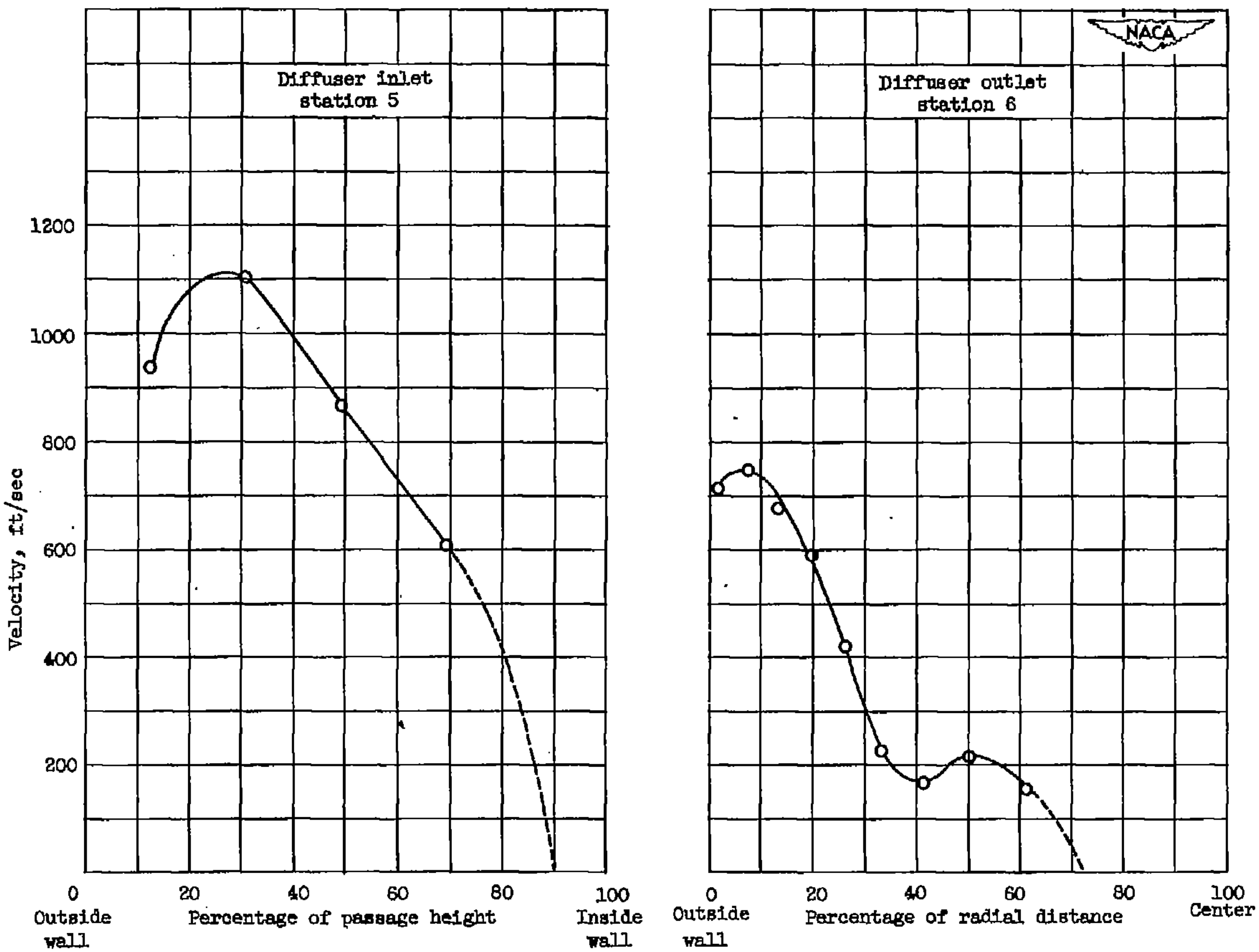


Figure 17. - Burner-inlet diffuser velocity profiles at inlet and outlet. Engine speed, 7900 rpm; flight Mach number, 0.60; altitude, 30,000 feet; exhaust nozzle closed (no burning).

[redacted]

2176

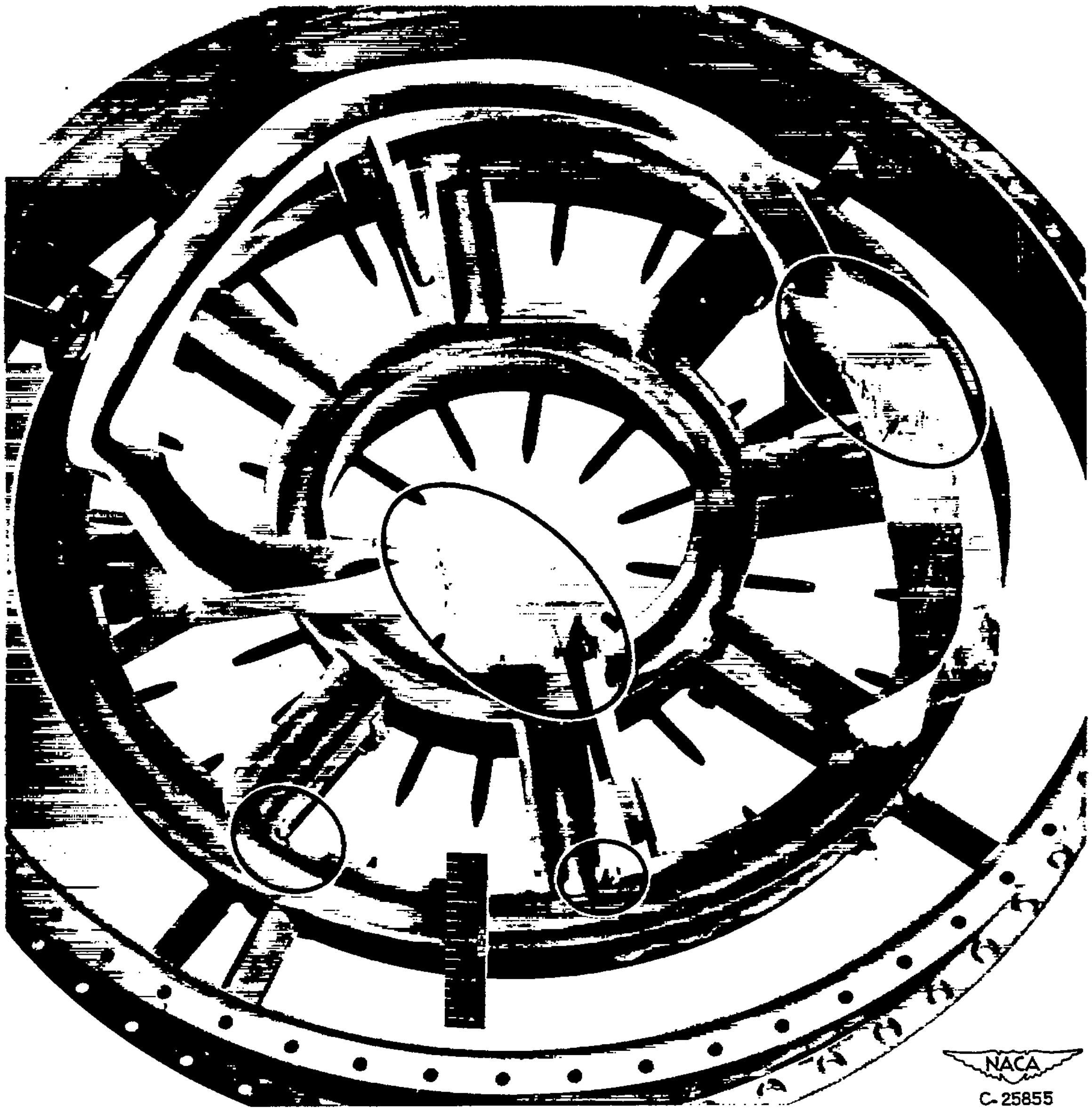


Figure 18. - Typical H-gutter failure and trailing V-gutter failure at intersecting gutters and support.

2176

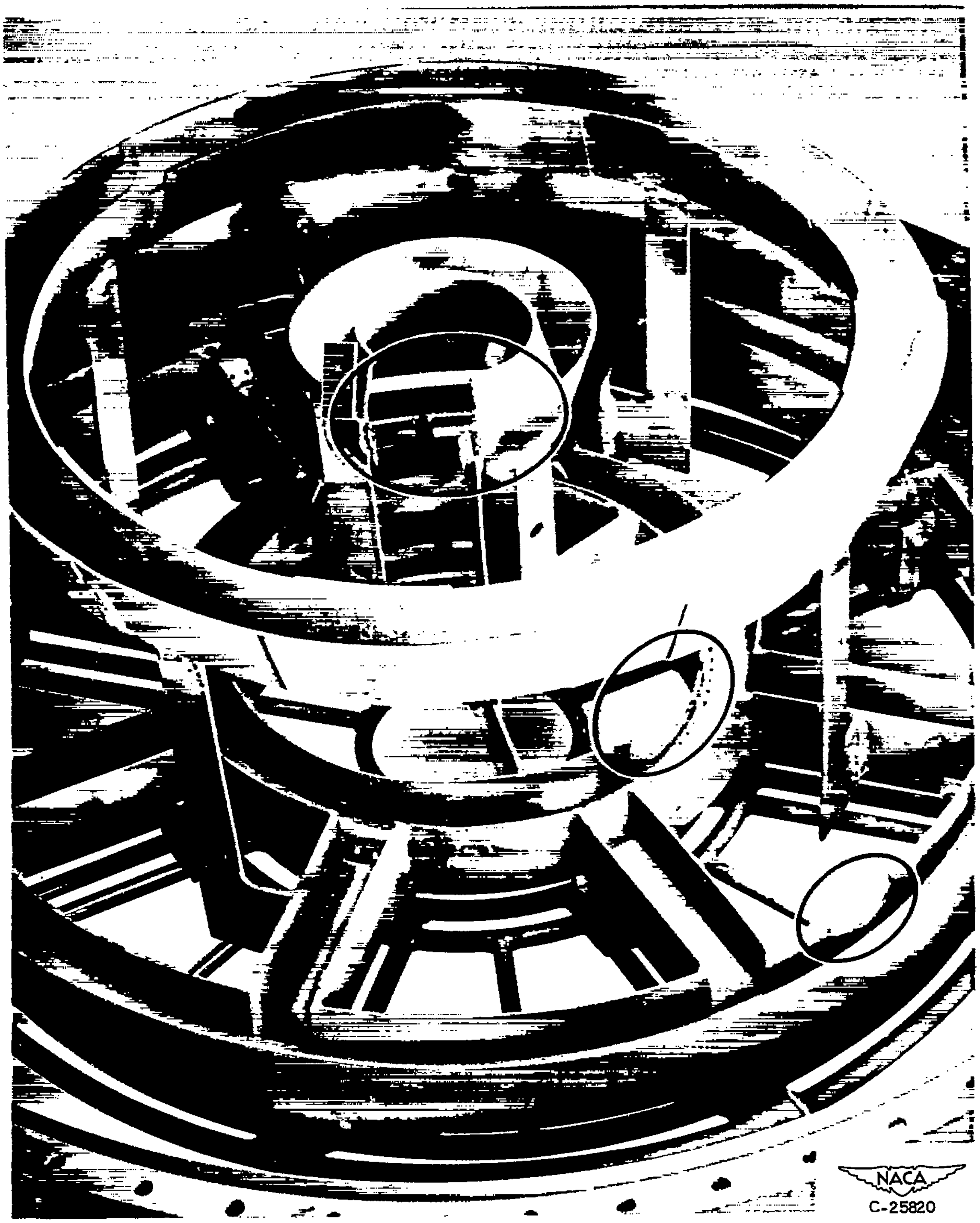


Figure 19. - Typical H-gutter failure and trailing V-gutter failure on surfaces not obstructed by intersecting gutters.

2176

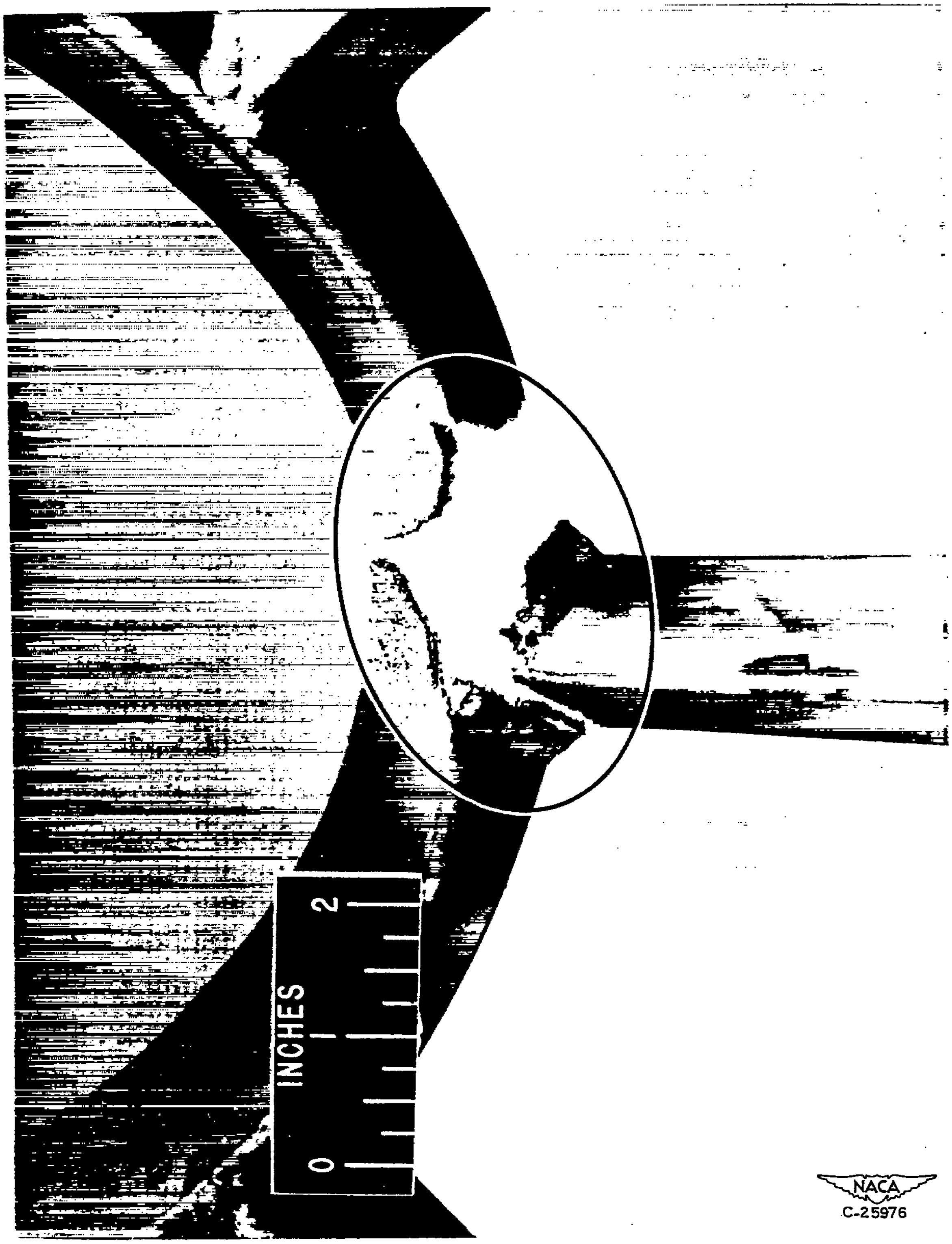
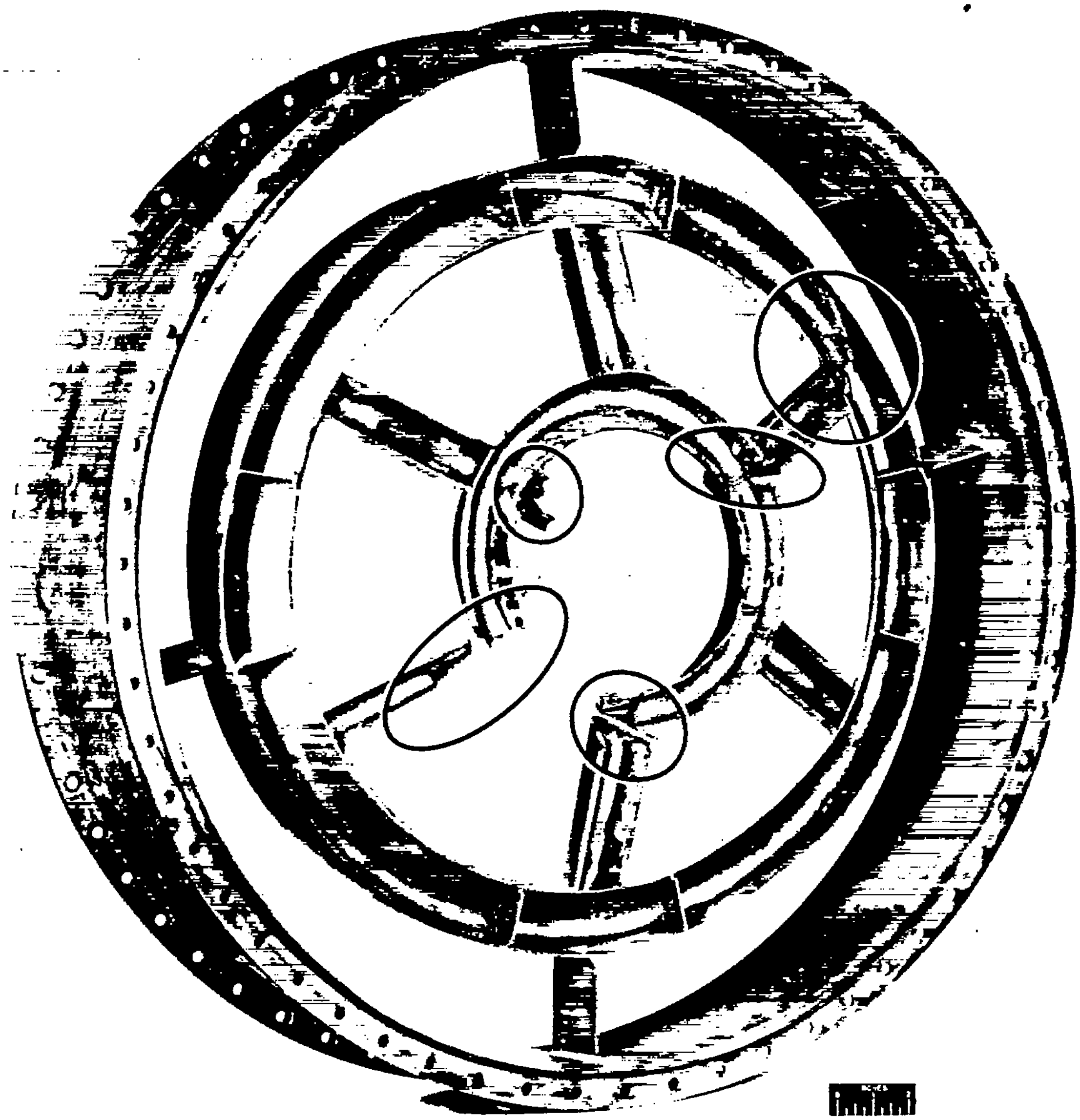


Figure 20. - Typical V-gutter failure at a gutter intersection.

2176



C-26050

Figure 21. - Typical V-gutter failure at gutter intersections and in sheltered region.

NACA-Langley - 12-11-51 - 430